A STUDY COMPARING CHANGES IN LOADING CONDITIONS OF AN EXTENDED SERVICE LIFE SYSTEM USING ALUMINUM 2024-T351

by

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The University of Utah Graduate School

STATEMENT OF THESIS APPROVAL

The following faculty members served as the supervisory committee chair and members for the thesis of _______Roger Zack Beal______________.

Dates at right indicate the members' approval of the thesis.

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The thesis has also been approved by ___Timothy A. Ameel________ Chair of the Department/School/College of ________Mechanical Engineering_______ and by David B. Keida, Dean of The Graduate School.

ABSTRACT

The current fiscally austere environment prevalent in the military and industry is driving extreme measures to save money. In the United States Air Force, this has driven enormous efforts to trim sustainment spending on extended life aircraft. The challenge to the aerospace engineer is to ensure flight safety in the midst of this economic pressure.

One method of cutting costs is to increase the time an aircraft is in service by delaying the point when the aircraft is taken out of service for depot maintenance. To ensure flight safety, in depth fatigue and fracture analysis needs to be accomplished to assess increasing the inspection interval.

The purpose of this study was to determine the sensitivity of Aluminum 2024-T351 alloy, a common material used in tension dominated aerospace applications, to two different loading spectra--one that is aggressive and the other that is benign. This was accomplished by conducting five different combinations of the two spectra, developing computer simulations using the AFGROW software and comparing with the measured data. The results showed that the material demonstrated significantly different behavior between the two spectra. These results provide a valuable tool for the aerospace engineer for fatigue life prediction and inspection interval evaluation.

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CHAPTER 1

INTRODUCTION

The increase of reliability and technology has enabled consumers to expect the products they use to last longer. An example is in the automobile industry where 100,000 miles was once considered the upper limit of the usable automobile life and today 200,000 miles is the expected norm. The aerospace industry is another area where usage life has exceeded the original design life. Commercial and Military aircraft, such as the Boeing 707 and 727s KC-135 and the B-52, respectively, have all outlived the life originally predicted by designers.

At the time of this writing, the move in our society and government for more fiscal responsibility is requiring deep budget cuts. This has resulted in enormous impact to the military aerospace environment. This has forced congressional and military leaders to make a choice between funding existing, termed Legacy, military aircraft or investing in next generation military aircraft. The decision, for the moment, involves cutting funding for Legacy aircraft. This is unfortunate because during the time leading up to this budget crisis, the demand on extending the life expectancy of legacy aircraft was high since the emerging new generation aircraft were behind schedule and over cost.

Until recently, namely the 2012-2014 time period, cost saving strategies by military and government leaders have driven the decision to retain military aerospace vehicles well beyond their designed service life. In a 2011 report by the United States Air Force Scientific Advisory Board, "according to the latest Department of Defense Aircraft Procurement Plan (Fiscal Years 2012-2041), the United States Air Force (USAF) will operate many of its aircraft well beyond their original design service lives." These life extensions would not be possible without the disciplined application of structural integrity programs such as the Aircraft Structural Integrity Program (ASIP). Two conclusions from the SAB study were to:

(1) Bring the newer integrity programs up to the same level of rigor that is evident in the more mature ASIP and PSIP programs.

(2) Explore specific technologies that might enhance the prediction capability for life of aging parts and subsystems.[1]

An important step toward enhancing the prediction capability for the life of aging parts and subsystems is to assess the impact of usage load changes on the design material. This cannot be characterized *a priori* but must be conducted by coupon testing, specifically fatigue testing, and the material response must be analyzed. This report will outline the methodology and supporting science that were used to characterize the effect of changing the loading environment on the material of an extended service life aircraft. A similar evaluation was conducted on 17-7 steel representing a different type of aerospace structure.[2]

1.1 Fatigue

Fatigue and corrosion are major failure modes for extended service aircraft. Both are sensitive to changes in environment but this study is focused on the effects of short term changes in loading environment. The definition of fatigue according to American Society of Testing Materials(ASTM) E1823, is "The process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations."[3]

The first recorded account of fatigue testing is attributed to W.A.J. Albert, a civil servant for mines in Hanover, Germany in 1837, for his work on fatigue testing of chains used in the Clausthal mines. During the 1858-1870 timeframe, August Wohler was an instrumental and influential early pioneer in the characterization of fatigue, developing service life analysis of railroad axles based on fatigue testing. According to Walter Schutz, author of History of Fatigue, "Wohler differs from all of his predecessors -- and most of his successors, some of them to this day -- in that he always had in mind the basic problems the engineer must solve when designing for fatigue: the service loads and stresses, and the endurable and, derived therefrom, the allowable stresses must be known."[4] The safe life fatigue design philosophy was based on fatigue loading to failure with a safety factor to allow for variability. Often, failure was defined as fracture but this definition was not consistent. This approach has proven to be unsatisfactory in that it assumes the product components are pristine and does not allow for characterization of the discontinuity state of the material. Furthermore, it does not require inspection of the part. As a result of aircraft accidents due to fatigue, the F-111 failures shortly after entry into service as an example, the US Air Force has adopted the Damage Tolerant Design Philosophy.

1.2 Damage Tolerant Design Philosophy

The damage tolerant design process outlined in Figure 1 is the design approach that acknowledges crack-like discontinuities being present in newly manufactured products. From the 1984 USAF Damage Tolerant Design Handbook "it is essential that safety of flight be provided through the consideration of an initial flaw model which some size of initial damage is assumed to exist consistent with the inspection capability either in the field or during manufacture. The critical assumed initial damage shall be considered to be that damage just smaller than can be detected by the appropriate NDI methods."[5] This philosophy differs greatly from the Safe Life philosophy which "assumes that the material being utilized is flaw free or at least operating at a stress level that is too low to propagate any flaws if they do exist."[6]

The terminology of "initial flaw" is misleading in that it has legal liability implications and a more accurate term is crack-like discontinuities to describe the variability of materials due to internal discontinuities. The term "initial flaw" will be used only in reference to US Air Force Damage Tolerant policy.

According to the Damage Tolerant Handbook, the key parameters that effect the crack growth model are the quality (initial crack size), usage (loading history), material (material properties), and geometry (structural properties).[7] The main areas of focus for Damage Tolerance involve 1) continual assessment of Residual Life based on Fatigue Crack Growth Analysis, 2) conducting Non-Destructive Inspection (NDI) according to inspection intervals derived from Fatigue Crack Growth Analysis to obtain data on crack growth in critical components and 3) aircraft monitoring of loading environment. This research will focus on the effect of a change in load history at crack sizes and the resulting material response of Aluminum 2024-T351.

1.2.1 NDI and Inspection Intervals

The US Air Force uses experimentation of representative specimens and analytical tools, with an assumed starting crack of an initial size of 0.05 inch for critical components as input, to develop the final fatigue fracture crack length. Through analysis of these data and a scatter factor to account for variability, the Service Exposure Time Period in Figure 2 is determined. To ensure flight safety, the inspection interval is determined based on the fatigue crack growth and the criticality of the component by dividing the Service Exposure Time Period into segments to conduct NDI. The significance of this experiment is to assess the impact of load history changes on the inspection interval between two loading spectra.

The “initial flaw” size is determined with input from the NDI community based on the accuracy of the inspection techniques such as bolt hole eddy current, x-ray, dye penetrant, and magnetic particle inspection. This limiting factor determines the smallest size of crack-like discontinuity that can be reliably detected with a specified degree of confidence. This lower limit and degree of confidence are determined statistically to define the Probability of Detection (POD) for each technique. The inspection technique and the related POD are incorporated into the Damage Tolerant Approach. The two NDI components allow for a starting point for the Damage Tolerant analysis to predict the fatigue life using Linear Elastic Fracture Mechanics (LEFM).

1.2.2 Fracture Mechanics Review

The advent of Fracture Mechanics in the 20th century was monumental and the foundation of Damage Tolerance design. The two pioneers in the field of fracture mechanics were C.E. Inglis and A.A. Griffith.

In his paper, “Stresses in a Plate due to the Presence of Cracks and Sharp Corners,” Professor C.E. Inglis modeled the stress and strain field around a crack using an ellipse as a geometrical model and curvilinear coordinates as depicted in Figure 3.[8]

This mathematical model provides the framework for mathematical modeling and the notation and geometry is used in this experiment.

In his work, “The Phenomena of Rupture and Flow in Solids,” Griffith expanded on this and established the following criterion for the propagation of a crack: “A crack will propagate when the decrease in elastic strain energy is at least equal to the energy required to create the new crack surface.”[9]

With the Inglis derived mathematical model of stresses and strains of an elliptical crack length of 2*c* defined by elliptical coordinates, Griffith was able to derive the elastic strain energy per unit of plate thickness with the following equation:

$$U_e = \frac{-\pi c^2 \sigma^2}{E} \qquad 1.1$$

where E is the Modulus of Elasticity, and σ is the applied stress, and c is the half length of the focal line of the crack modeled as the ellipse. In practical terms it is half the length of the total crack length 2*c*. The designation c was used in the original Griffith report but later convention changed the term to *a*.

The negative sign convention is used because fatigue crack growth results in a loss of elastic strain energy in the material.

He derived, by experimentation, the surface energy due to the presence of the crack is

$$U_s = 4c\gamma_s \qquad 1.2$$

where γ_s is the surface tension of the material

Therefore, the total change in potential energy resulting from the creation of the crack is

$$\Delta U = U_s + U_e \qquad 1.3$$

According to the Griffith's criterion, the crack will propagate under a constant applied stress if the incremental increase in crack length produces no change in the total energy of the system meaning the reduction of strain energy is equal to the surface energy.

$$\frac{d\Delta U}{dc} = 0 = \frac{d}{dc}\left(4c\gamma_s + \frac{-\pi c^2\sigma^2}{E}\right) \qquad 1.4$$

By rearranging the above equation, we have

$$\sigma = \sqrt{\frac{2E\gamma_s}{\pi c}} \qquad 1.5$$

This equation provided the foundation of fracture mechanics because it defined the stress to grow a crack with the crack size and the material properties.

Griffith chose glass as his experiment material because his analysis was restricted to materials operating in the elastic stress strain region, commonly referred to as brittle materials.

This approach was modified by Orowan and Irwin to apply to both brittle materials and metals that exhibit plastic deformation.[10] The modification established that a material's resistance to crack growth is determined by the sum of the surface energy and the plastic strain work. For ductile materials, the surface energy can be neglected.

Irwin also redefined the Griffith Equation as the Stress Intensity Factor (SIF)

$$K = \sigma\sqrt{\pi a}\, f(\frac{a}{W}) \qquad 1.6$$

where $f(\frac{a}{w})$ is a dimensionless parameter depending on the geometry of the specimen.[10]

The reference geometry of a center elliptical crack with a length of 2a in an infinite plate under uniform tensile loading has $f(\frac{a}{w}) = 1$. The common notation for this factor $f(\frac{a}{w})$ is Beta β.

1.2.3 Fatigue Crack Growth Analysis

Utilizing the methodology of fracture mechanics, the analyst can develop analytical solutions or models to match the fatigue crack growth data from testing. Tremendous work has been conducted in the last half century for developing new methodologies for characterizing geometries and materials. The Air Force and commercial transport industry structural analysts use fatigue crack growth models to predict fatigue life for critical locations in aircraft. The stages of fatigue life based on crack growth are shown in Figure 4.

With respect to loading history, early fatigue crack growth modeling effort utilized constant amplitude loading shown in Figure 5 (a) for ease of crack propagation estimation. Later models better approximated the actual loading environment referred to as Spectrum Loading shown in Figure 5 (b). The constant amplitude load model does not approximate actual load sequence of varying peak and valley loads depicted in Figure 5 (b) but is still used because it allows for simple computation using the crack length *a* and cycles *N* to calculate crack growth rate d*a*/dN. It is also convenient to describe the loading environment by the use of the stress ratio $R = K_{min}/K_{max}$. Unfortunately, more realistic models that better fit the variable amplitude loading sequence in Figure 5 (b) are difficult to characterize using only cycle count and stress ratio parameters.

This fact was observed by D.V. Nelson and H.O. Fuchs in 1976 in their paper "Prediction of Fatigue Crack Growth Under Loading" where they state "Virtually all predictions of fatigue crack propagation to date have been concerned with load histories which can be characterized by cycles. For simulated aircraft loadings, crack growth has been calculated for varying layers of cycles, with attempts to account for crack retardation due to periodic tensile overloads. For random loadings, particularly those with load spectra describable by the Rayleigh distribution function, crack growth has been described in terms of equivalent root-mean-square cycles. However, little consideration has previously been given to crack propagation for those irregular loadings where the definition of a cycle is not straightforward."[11]

1.2.3.1 Spectrum Development

The Air Force utilizes a combination of recording methods from counting accelerometers to flight data recorders to capture load conditions such as the normal load factor (Nz), lateral load factor (Ny), pitch acceleration, and other parameters. Some utilize modern aircraft systems that provide operational flight conditions to on board data buses for collection. With the type of mission and gross weight, the load conditions can be developed into stress conditions for critical fatigue locations on the aircraft. The spectra for represent two different operational environments one that is considered typical and one that may be applied for a short period of time due to different operational requirements.

In our experiment, the two spectra were called Spectrum A, representing an aggressive loading environment and Spectrum B, a benign loading environment. The two spectra are shown for comparison of severity in Figure 6, where Spectrum A has over 10 endpoints exceeding a load of 40,000 lbs and over 15 compressive loads while Spectrum B has only one endpoint load exceeding 35,000 lbs and 3 compressive loads. The Spectrum A represents more aggressive maneuvers per block at 14,737 endpoints per 240 EFH while Spectrum B represents a more benign flight profile per block with only 4,373 endpoints per 1000 EFH.

1.2.3.2 Crack Tip Plasticity and Fatigue Crack Growth Retardation

Because the focus of this research is on different loading environments and the potential for differences in crack growth retardation which is influenced by the material behavior at and beyond the crack tip, referred to as the plastic zone, a detailed review of crack tip plasticity is provided herein. The models describing the plastic zone fall into two main categories:

- Estimate the size of a zone with an assumed shape
- Shape is determined from a first order approximation to the size

The two most referenced models for the first category are those developed by Irwin and Dugdale. The work of Irwin recognized that the effective crack length is effectively longer than its physical size. The mathematical representation of that is

$$a_{eff} = a + \Delta a_n \qquad 1.7$$

where a_{eff} is the notional crack length and Δa_n is the notional crack increment.

For this effective crack length, the size of the plastic zone is defined by the equation below

$$r_y = \frac{1}{2\pi}\left(\frac{K}{\sigma_{ys}}\right)^2 \qquad 1.8$$

The plastic zone size ahead of the crack tip is shown for a cross sectional thickness in Figure 7. The plastic zone size according to Irwin is shown graphically in Figure 8. An important assumption for this theory is that the specimen is in the plane stress state condition.

The Dugdale model, like the Irwin model, was based on the assumption that the effective crack length is longer than the physical length, but assumed that the plastic zone ahead of the crack tip was a strip of length r_y shown in Figure 9. The Dugdale equation[12] assumes that the component is in plane stress.

$$r_y = \frac{\pi}{8}\left(\frac{K_I}{\sigma_{ys}}\right)^2 \qquad 1.9$$

The second category of shape theory is best modeled by the Von Mises Yield Criterion that yielding will occur when this equation is satisfied

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_{ys}^2 \qquad 1.10$$

where σ_1, σ_2 and σ_3 are the principal stresses.

For the 2-dimensional case, the mode 1 stress equations are

$$\sigma_1 = \frac{K_I}{\sqrt{2\pi r}} \cos {}^{\theta}/_{2} \, (1 + \sin {}^{\theta}/_{2}) \qquad 1.11$$

$$\sigma_2 = \frac{K_I}{\sqrt{2\pi r}} \cos {}^{\theta}/_{2} \, (1 - \sin {}^{\theta}/_{2}) \qquad 1.12$$

where $\sigma_3 = 0$ for plane stress.

By substituting the principal stresses into the yield criterion, the plane stress state size is determined by the dimensionless equation

$$\frac{r(\theta)_{\text{plane stress}}}{r_y} = \frac{1}{2} + \frac{3}{4}\sin^2\theta + \frac{1}{2}\cos\theta \qquad 1.13$$

Similarly, the plane strain size is determined by the dimensionless equation

$$\frac{r(\theta)_{\text{plane strain}}}{r_y} = \frac{3}{4}\sin^2\theta + \frac{1}{2}(1 - 2\nu)^2(1 + \cos\theta) \qquad 1.14$$

The Von Mises Yield Criterion is shown in the 2D form in Figure 10 and the 3D form in Figure 11. This characteristic shape was observed visually during this experiment.

The relevance of the plastic zone models mentioned above to fatigue crack growth analysis is that changes in the cyclic plastic zone due to tensile overloads often result in retardation or deceleration of successive crack growth until each crack growth increment exceeds the plastic zone increment. This phenomenon is displayed graphically in Figure 12. Therefore a sequence of loads with an “overload” followed by a series of lesser loads will develop a plastic zone retarding crack growth until the subsequent loads grow the crack through the plastic zone. This process is shown in Figure 13.

1.2.3.3 Previous Spectrum Research

The most simple and unfortunately unreliable models involve the so-called "Miner's Rule," named after Milton Miner from a computational method referenced in his report in 1945.[13] The method is summarized in the equation

$$\sum \frac{n_i}{N_i} = 1 \qquad 1.15$$

which states that if a structural component experiences fatigue loading with a constant stress amplitude S_{a1} over n_1 cycles with a fatigue life of N1 than that is equivalent to consuming n_1/N_1 of the fatigue life of the material. According to this damage accumulation concept, each block of constant amplitude loads contributes a fraction of fatigue damage to the total fatigue life. An example of two different constant amplitude blocks is shown in Figure 14.

According to J. Schijve,

> The fundamental shortcoming of the Miner rule is that fatigue damage is indicated by a single damage parameter only, n/N, which accumulates from zero (pristine specimen) to 1. Fatigue damage should be defined as comprising all changes in the material occurring as a result of the cyclic load. In addition to local decohesion (cracking), fatigue damage includes repeated crack tip plasticity, local stain hardening in the crack tip zone, residual stresses around the crack tip.[14]

The early variable amplitude loading models were based on constant amplitude loading with symmetric tensile peak loads interjected at regular intervals as shown in Figure 15.[15] An example of this method was used by J.M. Barsom where the root mean stress intensity was developed from the relationship shown below.[16]

$$\Delta K_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \Delta K_i^2} \qquad 1.16$$

However this method is only useful for load spectra that are uniformly distributed as shown in Figure 15. Furthermore, it does not incorporate the interaction effects.

The term “overload” is misleading in that it implies that a load is applied that exceeds the ultimate load of the material. This is not the case in spectrum loading. Rather, the term “overload” means a load that exceeds the previous set of maximum loads. Likewise, the term “underload” means a load that is less than the previous set of minimum loads. The values in Figure 15 relate to the stress intensities and stress ratio associated with overloads and underloads.

Some of the largest spectra research was accomplished by J. Schijve and his work is heavily referenced in this report. Schjive classified the models that include interaction effects into three categories: Yield Zone models, Crack Closure models and Strip Yield models.[17] The work of Elber is an example of a Crack Closure model where the material ahead of the crack is plastically extended in the direction of loading which retards fatigue crack growth as shown in Figure 16.[18]

Both the Willenborg and the Wheeler models were proposed to explain the crack growth retardation induced by high loads. Both models are based on an Irwin plastic zone shown in Figure 7 but Wheeler related the retardation to r_{yi}/λ and Willenborg made a different assumption about the effective stress as affected by the plastic deformation of the overload.

In the Generalized Willenborg model shown in Figure 17,[19] the retardation is characterized by the following equation: [20]

$$K_r = \frac{1 - \dfrac{\Delta K_{th}}{K_{\max}}}{(SOLR - 1)} \left[K_{\max}^{OL} \sqrt{\frac{1 - \Delta a}{r^{OL}}} - K_{\max} \right] \qquad 1.17$$

where the Shutoff Overload Ratio (SOLR) is defined as the maximum ratio of the overload maximum SIF to the subsequent maximum Stress Intensity Factor, K.

1.3 Research Project Outline

For this study, two spectra, A and B, were selected for analysis and comparison. Spectrum A represents an aggressive load history with many endpoints. Spectrum B represents a more benign load history with few endpoints. The goal is to assess how much effect the change in spectrum will have if the operating environment is changed from Spectrum A to B, for three life stages: early in product life, midlife and mature product life stage. Another way to consider this is that a change in operational environment can occur prior to crack detection, after detection, and after detection representative of a crack that was missed during its last depot maintenance. To relate this to fatigue life prediction, the graph in Figure 18 depicts the stages in fatigue crack life that will be referred to often in this paper. For this research the factor chosen to represent each stage of product life was the fatigue crack length crack relative to the thickness of the representative sample. The material for this experiment is 2024-T351 which is a common alloy used in tension dominated structural applications.

Each transition point in Table 1 represents the spectrum change combination in the research where the initial Spectrum A was changed to a new Spectrum B at a specified life phase (early, mid, mature life) based on specified fatigue cracks along the bore. This new spectrum represents a different operational environment or mission mix. The purpose is to characterize, for each phase of life, how the new spectrum affects the crack growth.

There were three replicates tested at each combination to validate the test process. For comparison, baseline fatigue crack testing to full fracture was conducted on Spectrum A and Spectrum B test specimens, with 3 replicates for each baseline test. The three combinations and the associated spectrum switch points are displayed graphically in Figure 18.

1.4 Research Project Objectives

The research objectives are listed below:

1) Utilize empirical methodology of characterizing fatigue crack growth under a change in spectrum loading by fatigue loading of specimens and using AFGROW for analytical modeling and assess the effectiveness of this method
2) Develop retardation models for Baseline A and B Spectrum Loading
3) Develop retardation models for Spectrum A+B Combinations 1, 2 and 3
4) Assess change in loading on inspection intervals and product life expectancy
5) Characterization of change in load history on retardation effects

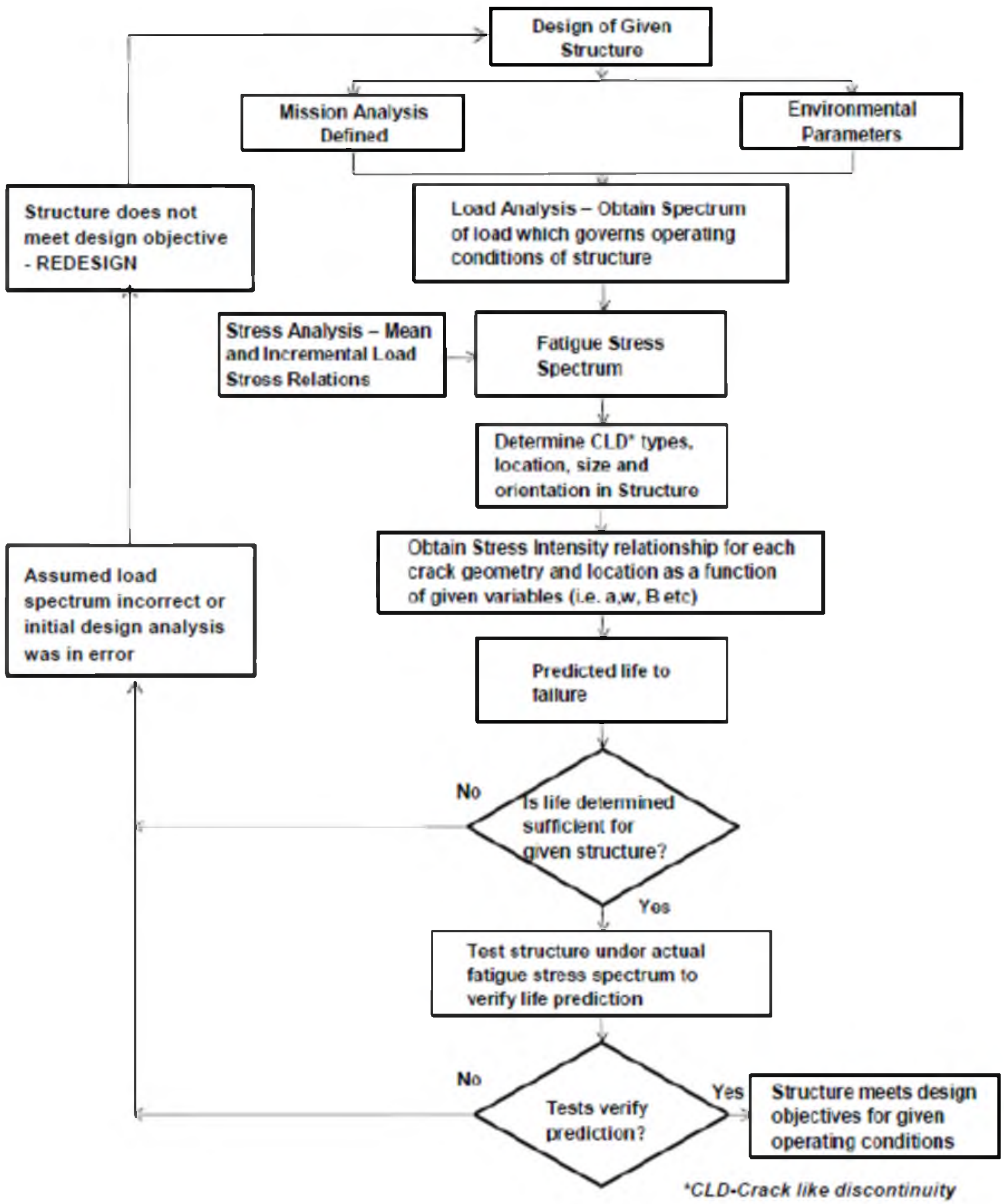


Figure 1 Damage Tolerance Design Flow Chart[21]

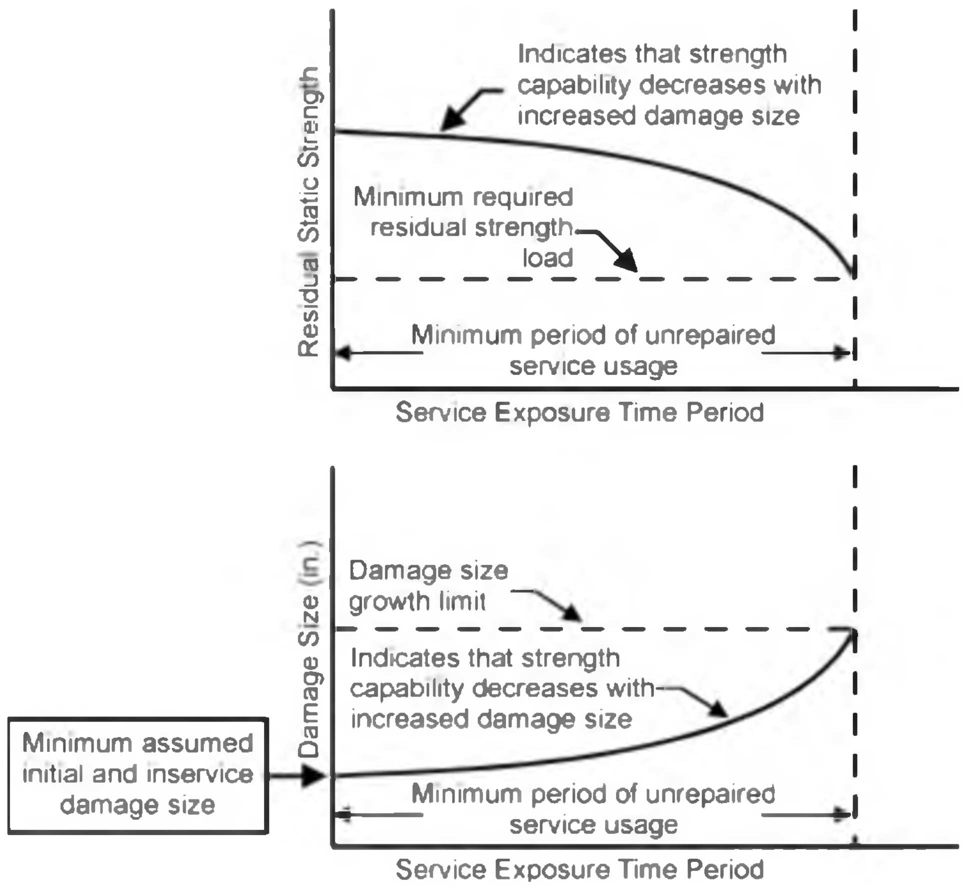


Figure 2 Service Exposure Time Period[22]

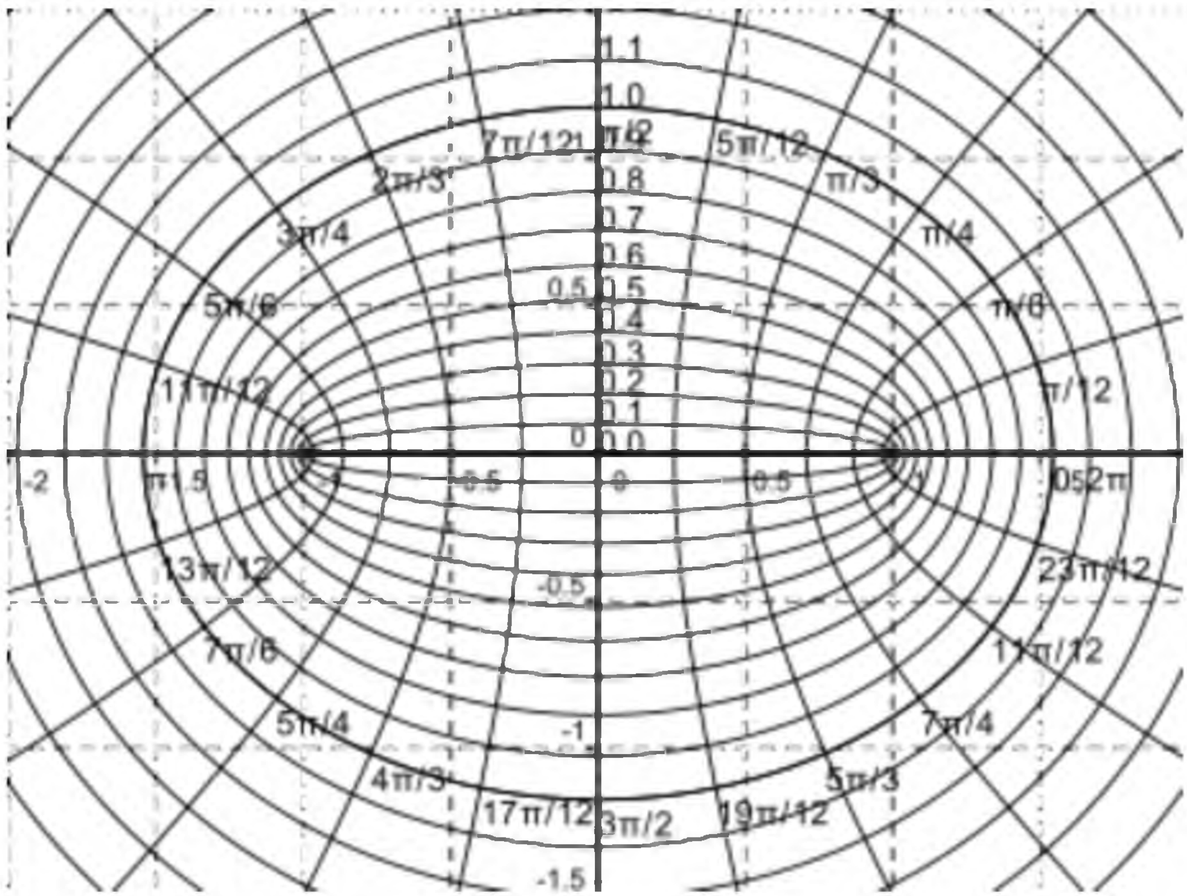


Figure 3 Elliptical Coordinate System[23]

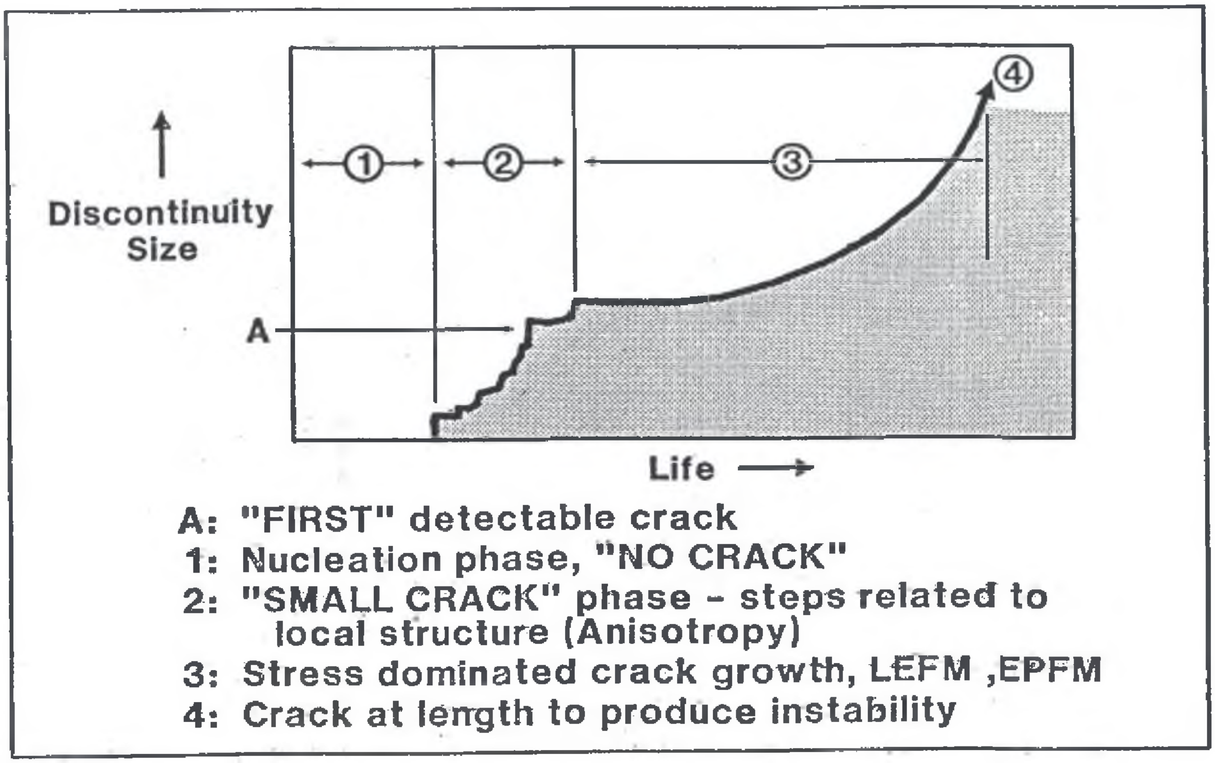


Figure 4 Crack Growth Life Curve[24]

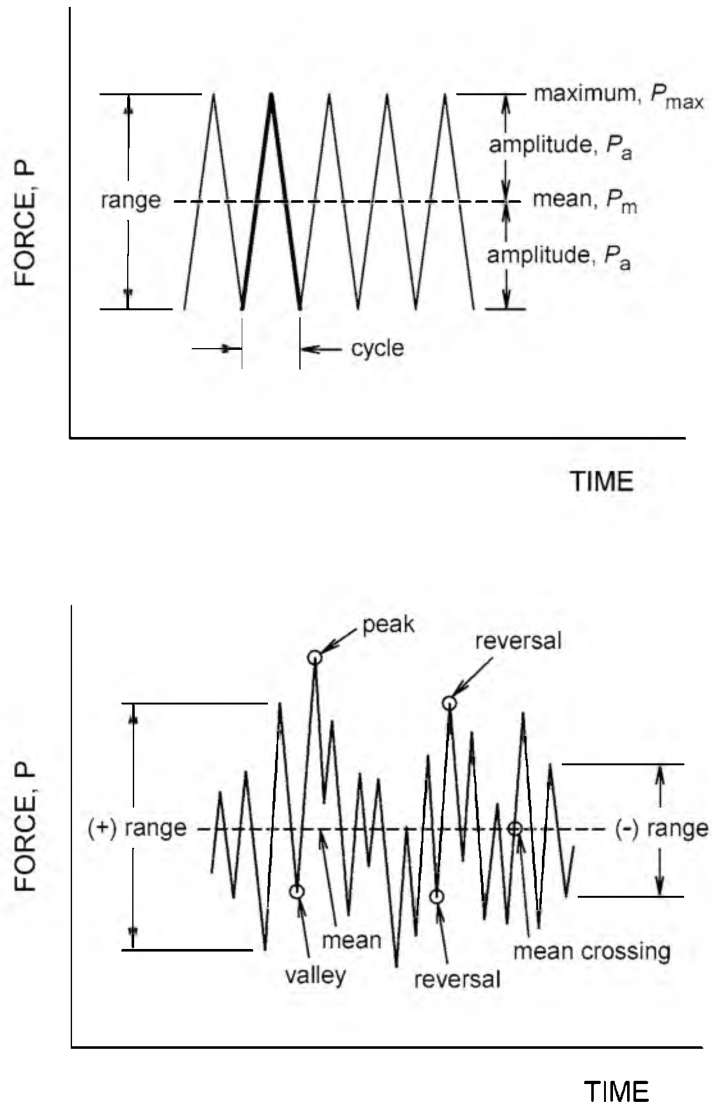
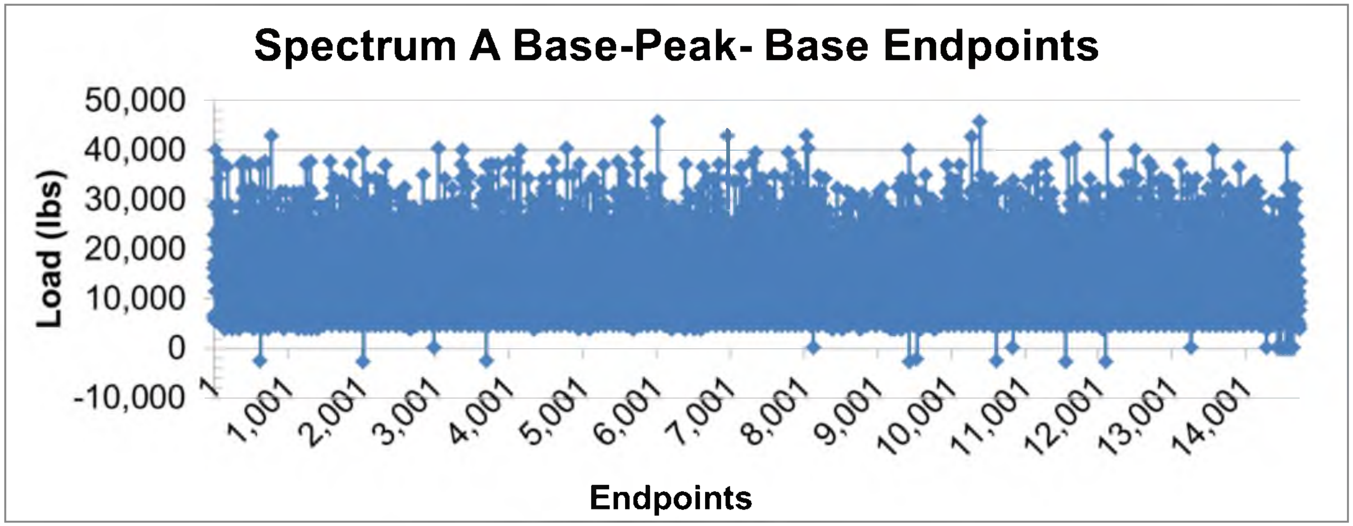


Figure 5 Constant Amplitude vs. Spectrum Loading



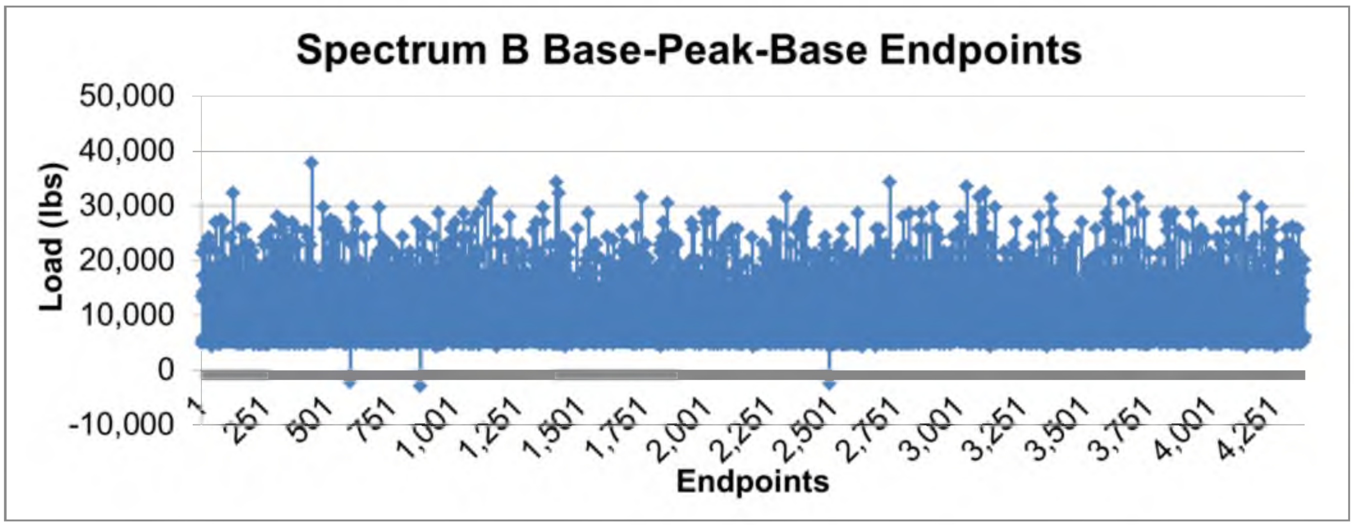


Figure 6 Complete Spectrum A and B for Comparison

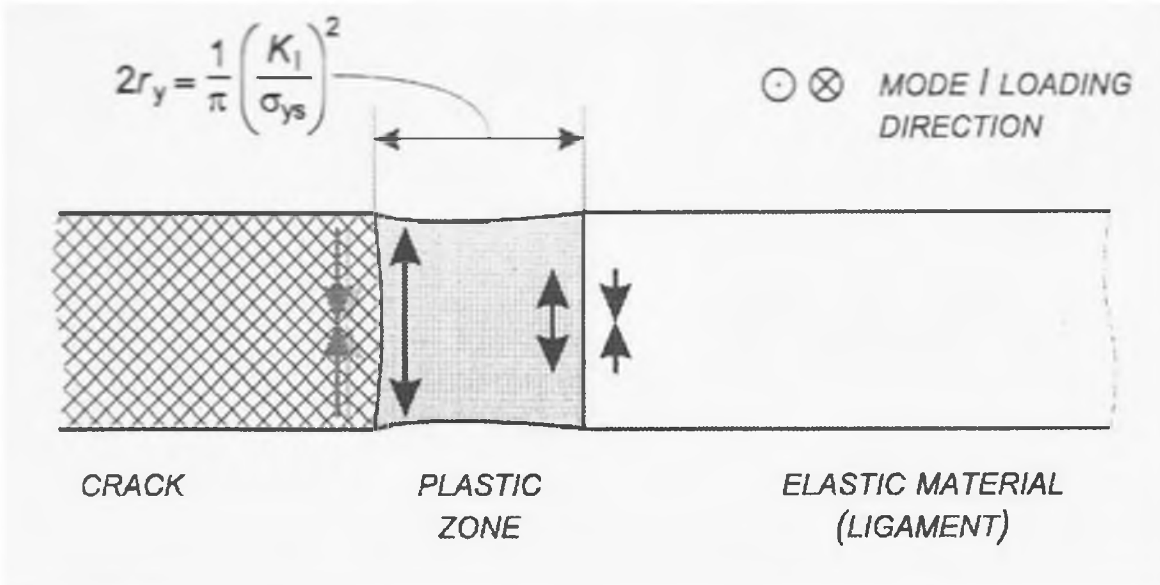


Figure 7 Irwin Crack Size (Profile View) [25]

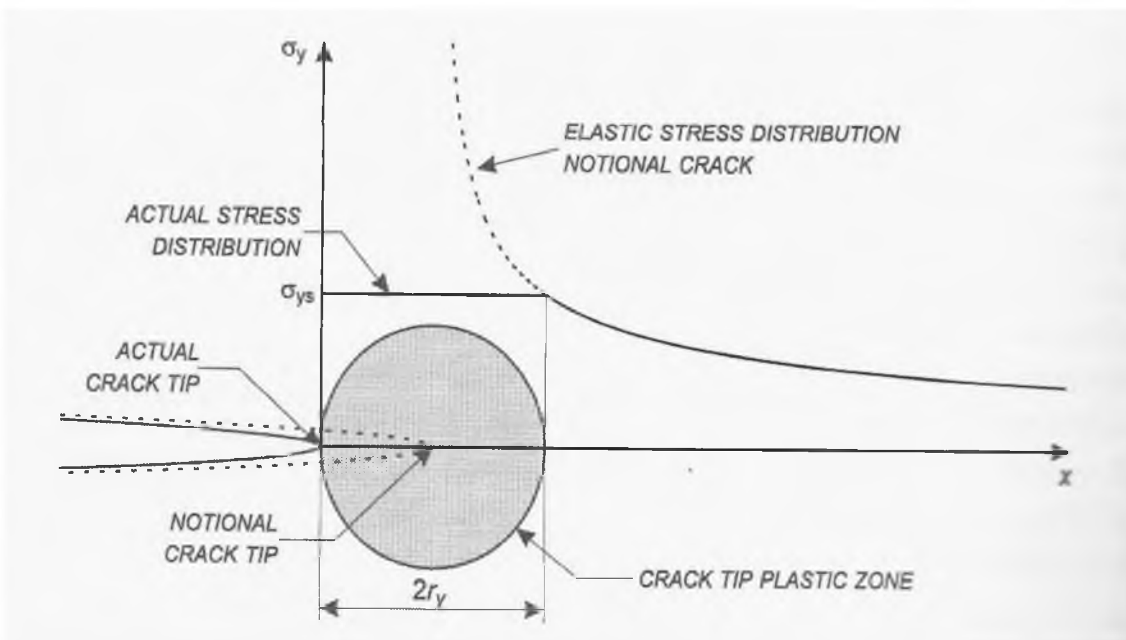


Figure 8 Irwin Plastic Zone Size [26]

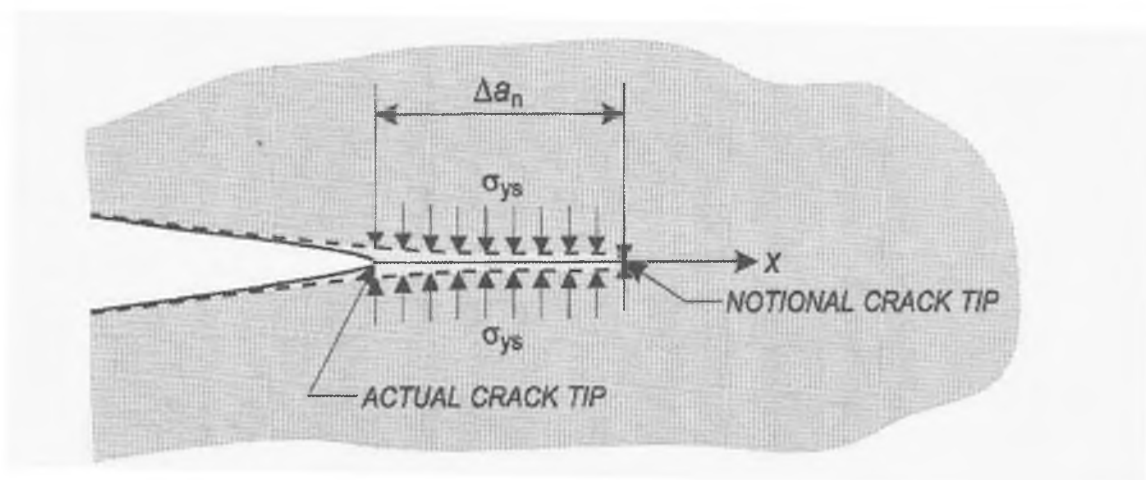


Figure 9 Dugdale Plastic Zone Size[27]

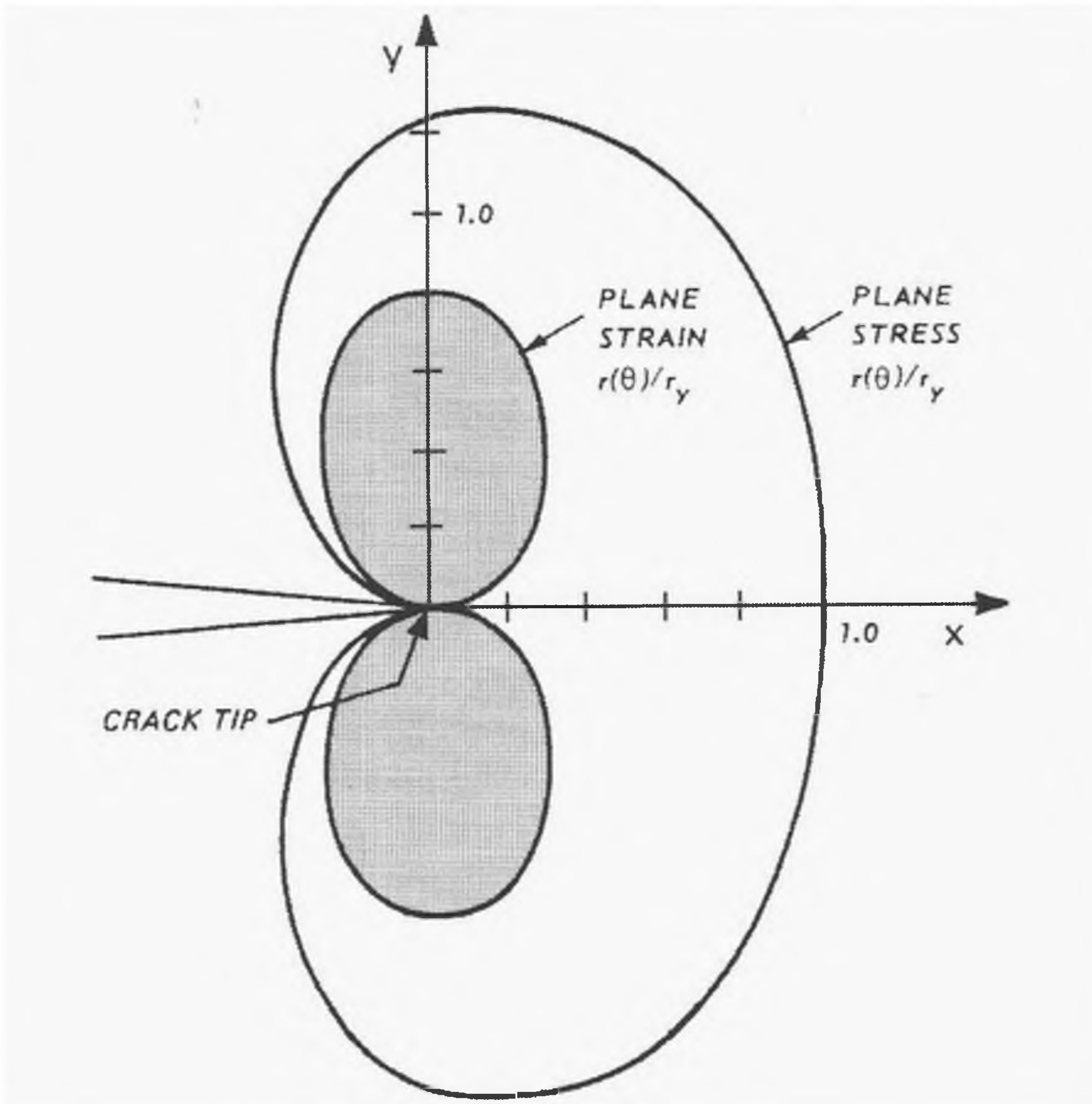


Figure 10 Von Mises Yield Criterion Plastic Zone Size[28]

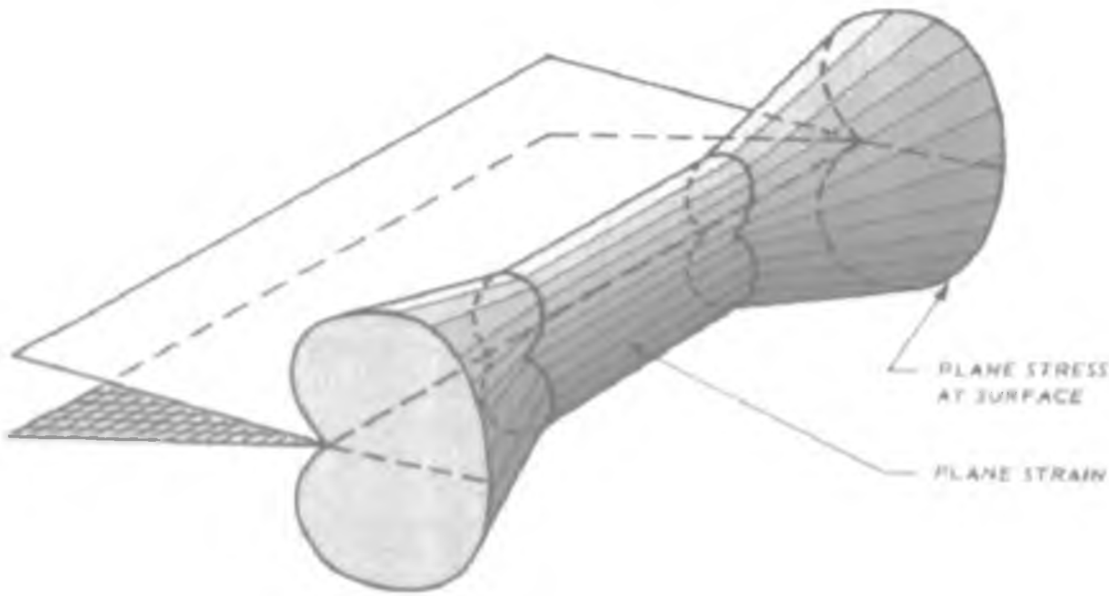


Figure 11 Three-Dimensional Von Mises Plastic Zone Size[29]

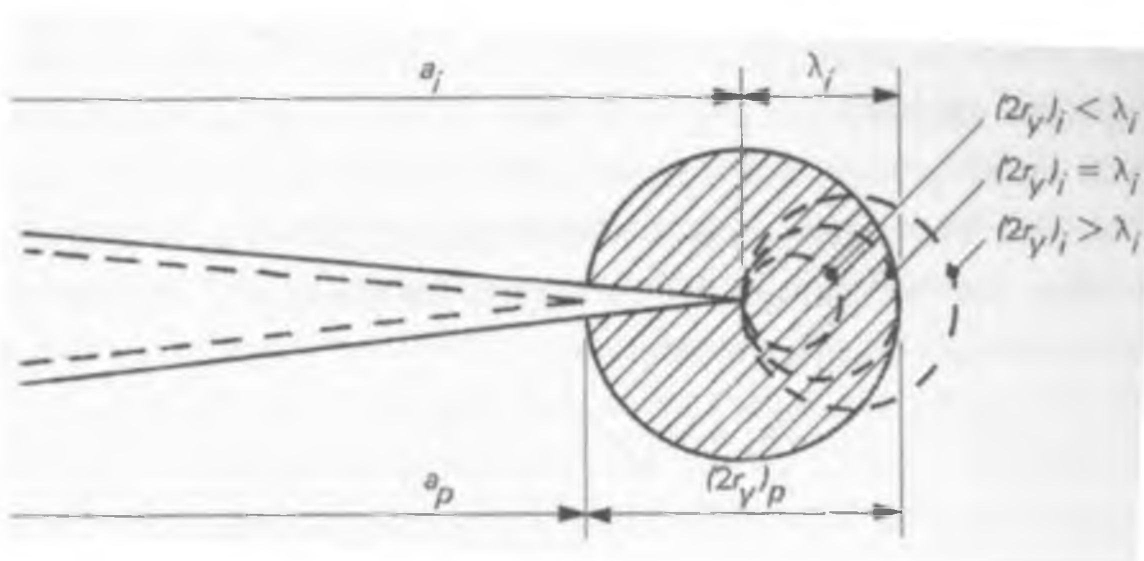


Figure 12 Crack Tip Plasticity Retardation Theory[30]

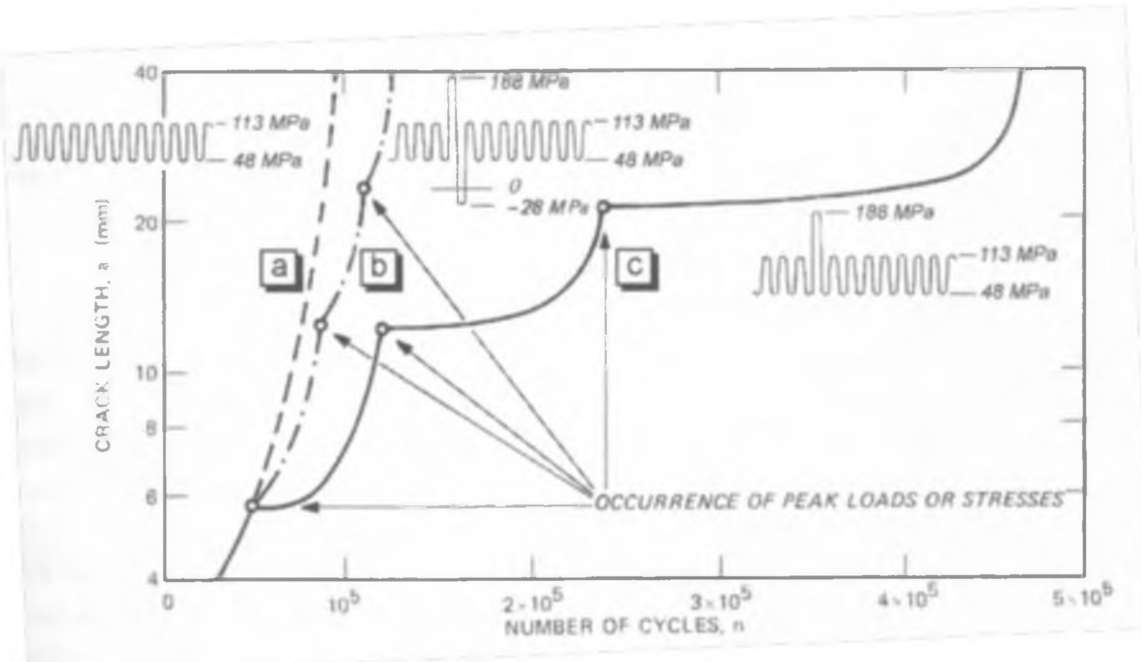


Figure 13 Crack Growth Retardation Due to Overload[31]

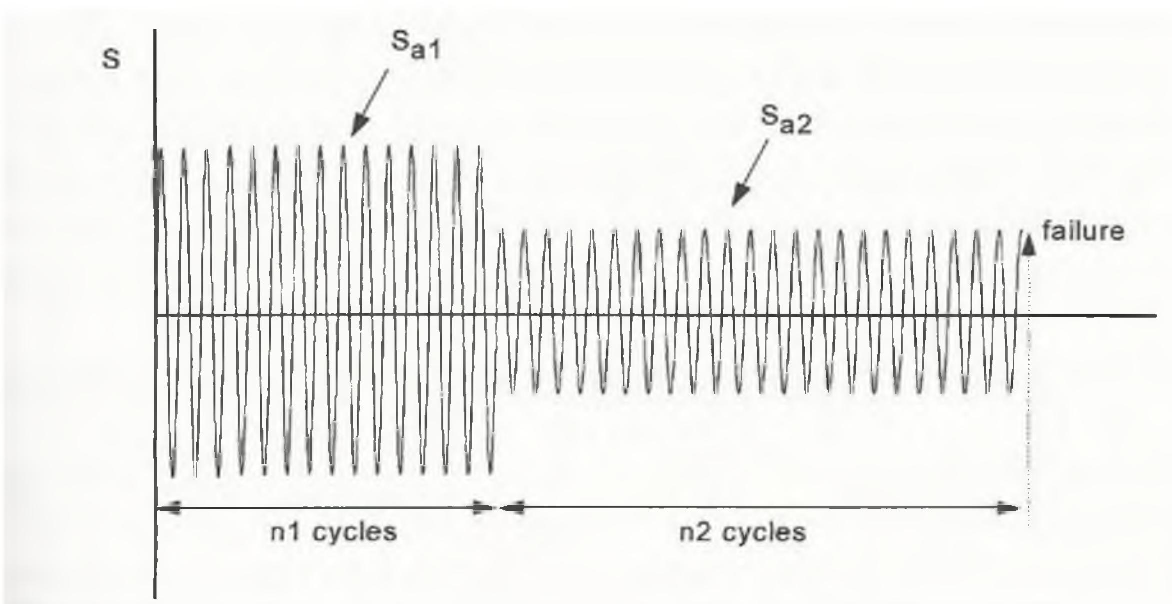


Figure 14 Two Consecutive Constant Amplitude Blocks[32]

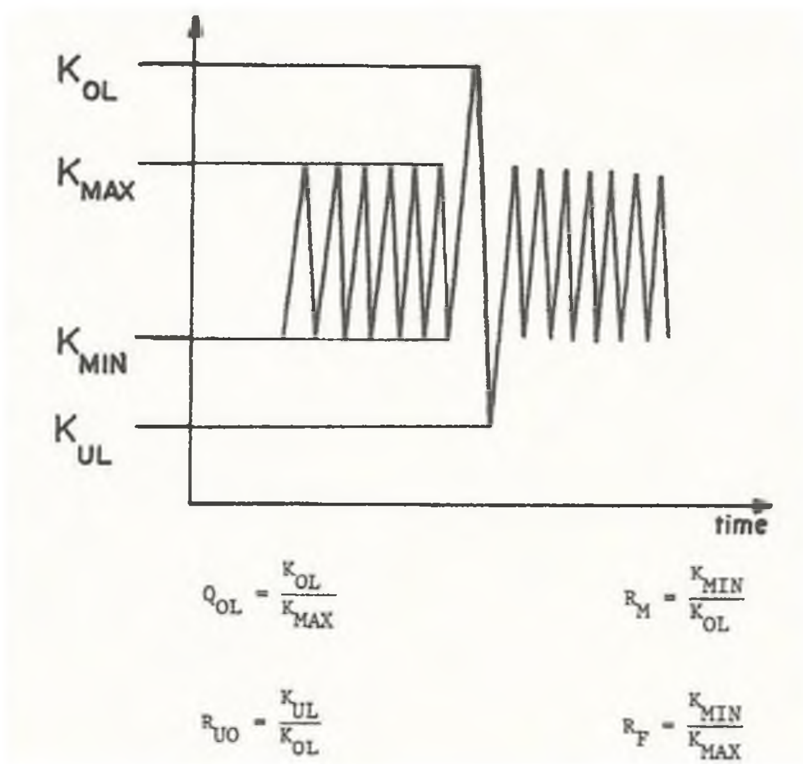


Figure 15 Constant Amplitude Loading with Single Overload and Underload Cycle

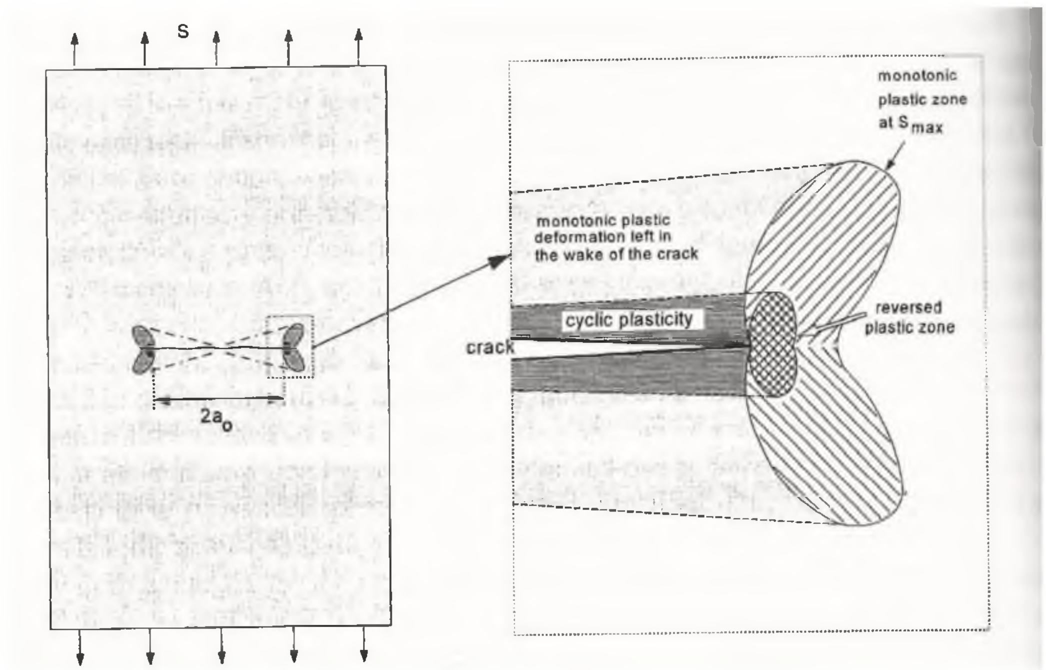


Figure 16 Elber Crack Plastic Zone

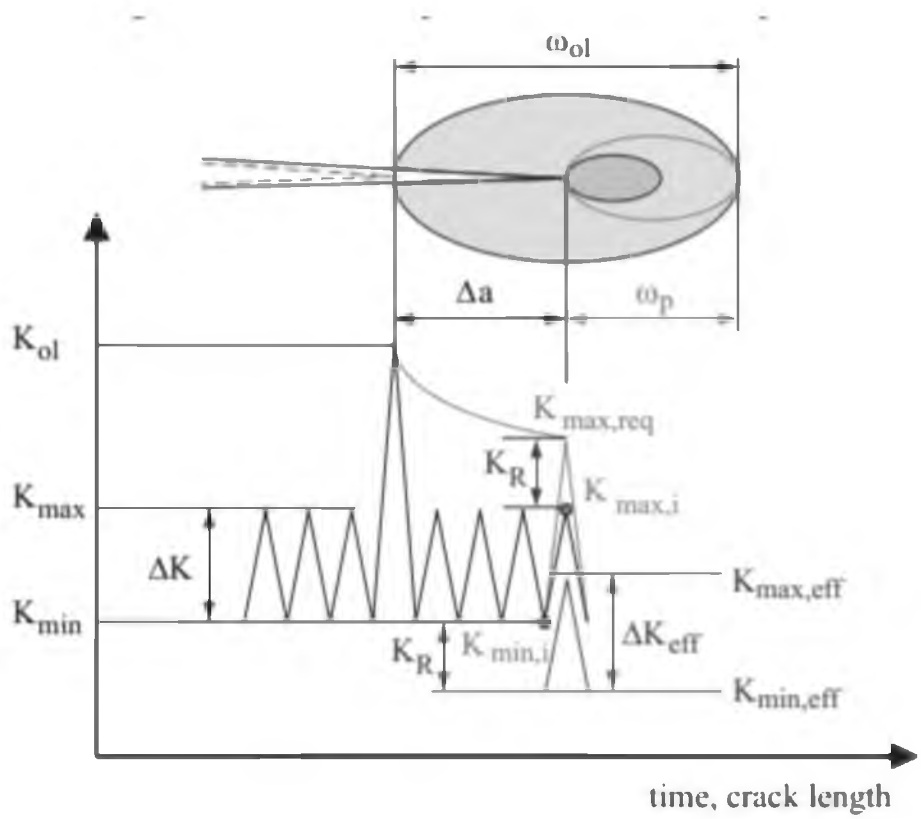


Figure 17 Generalized Willenborg Model

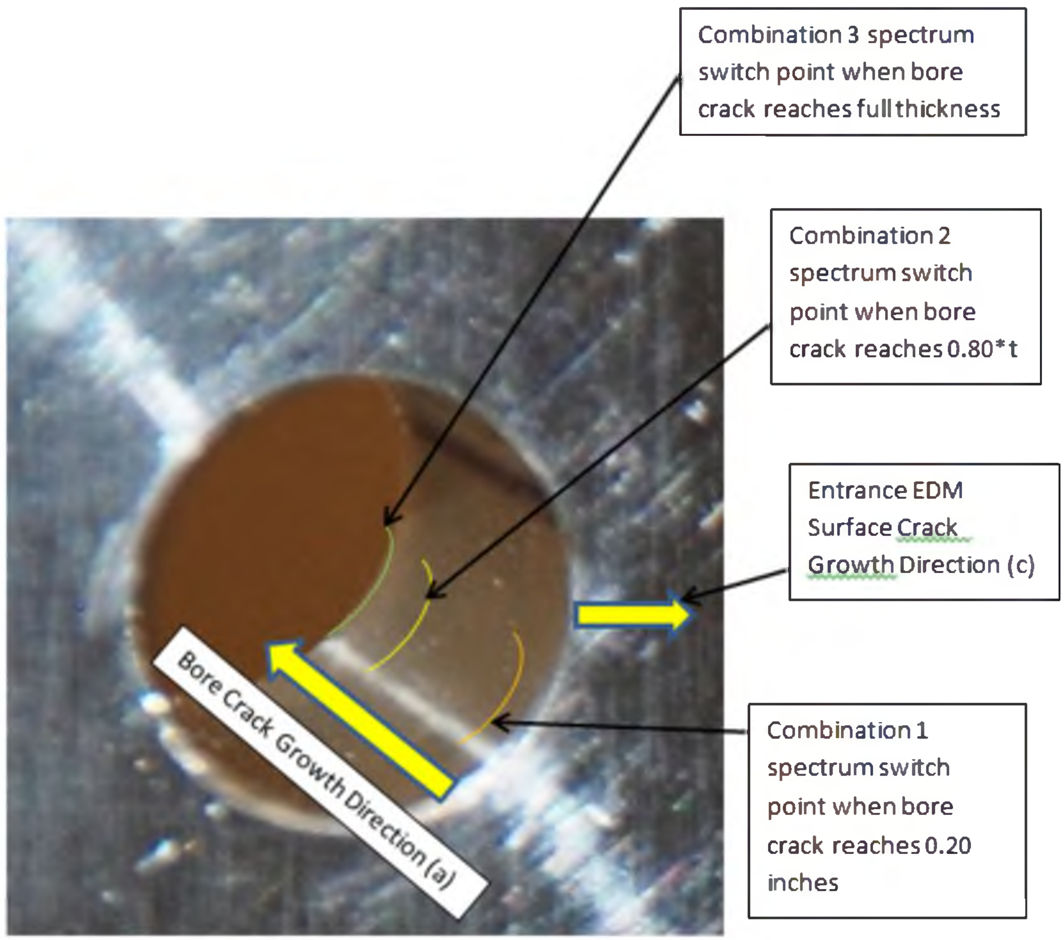


Figure 18 Bore Crack Spectrum Combination Switch Points

Table 1 Experiment Spectrum Combination Matrix

Combination	Type	Description	Actual Loading Environment	Change Over/Termination Point
Baseline Spectrum A	Baseline	Run only Spectrum A until Specimen Failure	Aircraft exposed to only Spectrum A Loading	None/Full Fatigue Fracture
Baseline Spectrum B	Baseline	Run only Spectrum B until Specimen Failure	Aircraft exposed to only B Spectrum Loading	None/Full Fatigue Fracture
A plus B 1	Mixed	Run A until crack in bore reaches 0.2 inches	Represents switching to Spectrum B loading early in aircraft life Slow crack growth region	Crack Bore reaches 0.2 inches/B reaches 100000 EFH or part fails
A plus B 2	Mixed	Run A until crack in bore reaches 0.8*thickness equal to .328 inches	Represents switching to Spectrum B loading in midrange of aircraft life Steady crack growth region	Crack Bore reaches 0.328 inches/B reaches 100000 EFH or part fails
A plus B 3	Mixed	Run A until crack in bore reaches through thickness Roughly .010 inches on back side	Represents switching to Spectrum B loading late in aircraft life Fast crack growth region	Crack Bore reaches 0.010 inches on back side/NT reaches 100000 EFH or part fails

CHAPTER 2

TESTING SETUP AND PROCEDURES

2.1 Test Specimen Specifications

2.1.1 Specimen Material

For the fatigue crack propagation evaluation, 2024-T351 aluminum plate (AMS-QQ-A250/4) was chosen as the material for this experiment to represent material typically used on components loaded under tension-dominated spectra. Since this study focuses on the material response under different spectra, the material properties are significant. This Aluminum 2024-T351 material is useful for this spectrum fatigue study in that the yield stress, from the material testing data sheet in Appendix A, of 57.4 KSI in the longitudinal direction, compared to the 17-7 PH CRES used in Tony Hyer's companion project of 195 KSI. Since the plastic zone sizes developed by Irwin and Dugdale are determined from the stress intensity and yield stress, it is expected that the Al 2024 will be more sensitive to overloads in the spectrum than the 17-7 PH.

Alloy 2024 was introduced by Alcoa in 1931 as an alclad sheet in the T3 temper. The material is shown in Table 2. It was the first Al-Cu-Mg alloy to have a yield strength approaching 50,000-psi and generally replaced 2017-T4 (Duralumin) as the predominant 2XXX series aircraft alloy. With its relatively good fatigue resistance, especially in thick plate forms, alloy 2024 continues to be specified for many aerospace structural applications.

The raw material was purchased by Northrop Grumman from Kaiser Aluminum on 9 Nov 2011. The material certification sheet is in Appendix A.

2.1.2 Test Specimen Fabrication

The specimens were manufactured per GT70KB003-11 drawing in Figures 19, 20, and 21 by the Northrop Grumman Technical Services Laboratory.[33]

For clarity, the manufacturing process is described in more detail and consisted of the following steps:

1. Cutting the specimens from the stock sheet from Kaiser Aluminum
2. Milling to dimensional specifications per GT70KB003-11
3. Shot Peening of both sides of the 4.0 inch x 4.0 inch end area according to AMS-13165 Table 6. This is to provide sufficient contact surface for the fatigue machine grips.
4. Drilling the undersized center hole to a diameter of 0.156 inches
5. Hand finish sanding in LT direction with 320 grit sandpaper to 125RHR or better
6. Electric Discharge Machining (EDM) of corner notch in hole per USAF A3G-2012-184383. This surface area is referred to as the EDM Entrance Surface throughout this paper.
7. Stamping the specification indication on both ends of specimen with engraver or vibra pen. This was useful for specimen identification after the part was fractured into two pieces.

Rolling direction was in the longitudinal (L) grain orientation, which is the load direction, to be consistent with the primary loading axis in application. The Short Transverse (ST) orientation is through the thickness. The material was Mill Tested according to ASTM E8/B557 and chemistry testing was accomplished according to ASTM E1251 by the Aero Specialties Material Corp. The material certification sheet data is shown in Appendix A.

The width and length of the specimens were based on guidance given in American Society for Testing and Materials Standard Test Method for Measurement of Fatigue Crack Growth Rates – ASTM E647. The thickness was chosen to match that of the application in question. The standard dimensions of the specimens were 16 inches long, 4 inches wide, and 0.410 inches thick. The specimens were of the Standard Center Hole Model with a Corner Crack model with an undersized starting center hole diameter of 0.156 inches. A starting EDM notch of 0.020 inches in the bore and 0.030 inches on the surface was produced on one side of the hole and perpendicular to the loading direction.

2.2 Test Equipment

2.2.1 Hill AFB Fatigue Machine and Equipment Specifications

2.2.1.1 Interlaken Series 3300 55 Kip Load Frame

The Interlaken Series 3300 55 Kip Load Frame, shown in Figure 22, was installed in 1992 at Hill AFB in Building 100. The Load Frame consists of an upper cross head assembly containing the model 1032AF-50K-B load cell and a lower actuator that has a +/- 3 inch travel with downward movement to induce tensile loading and upward movement for unloading/compressive loading. The upper cross head can move up or down to accommodate various lengths of samples and then is locked in place to react to the load applied by the lower actuator. The load cell provides the controller with the feedback of the actual load being applied to the specimen. The load cell and fatigue machine are calibrated every year, by the Instron Company, according to ASTM E4. The fatigue machine was calibrated on 4/15/13 and the load cell was calibrated on 4/16/13.

2.2.1.2 Instron 8800 Fast Track Controller and Software

The Instron 8800 Fast Track Controller and Instron Bluehill 2 software package were utilized for this spectrum research. The two Instron software packages that were used to run the fatigue experiment were the WaveMatrix and Random Loading packages.

The Instron WaveMatrix Software was used for constant amplitude loading during the precracking phase of the experiment. The inputs for this software are the cycle frequency in hertz, and the amplitude and mean load. For the precracking stage, all coupons were tested at 7 hertz with a mean load of 16.79 kips and an amplitude of 15.19 kips.

The Instron Random Loading software was used to find the points at which the hard worked area has failed for the variable amplitude phase of the fatigue testing. The software spectrum loading input is read from a file that has the spectrum load history, with the unit of pounds, in the form of load endpoints as shown in Table 3. These values, with the units of pounds, represent the first 14 endpoints of Spectrum A. These 14 endpoints, out of 14,373 total, from spectrum A, are shown graphically in Figure 23.

The Instron Random Loading Software screen is shown in Figure 24. The list of input options for the software program are included in Table 4.

This program controls the lower actuator input according to the input load value read from the spectrum file shown in Table 3. This corresponds to the command load shown in red in the screenshot of the program in Figure 24. The feedback load from the load cell on the frame is shown in white in the display screen. This phase shift is typical for servo-hydraulic test systems.

2.2.1.3 MTS Grips

The hydraulic MTS Model 647 wedge grips were used during the experiment to hold the upper and lower sections of the Center Hole with Single Elliptical Corner Crack Specimen. These grips have a 55 kip load capacity and can hold a specimen with a contact grip area that is 4 inches wide by 2.5 inches long.

2.2.1.4 MTS Hydraulic Intensifier

The incoming pressure from the Hydraulic Supply Unit (HSU) of 3000 psi is insufficient to for operation of the MTS Model 647 wedge grip requiring up to 5000 psi to prevent the specimens from slipping under maximum load. The MTS Model 685.60 hydraulic intensifier provides pressures to 5000 psi to provide the proper grip pressure to prevent the specimen from slipping.

2.2.1.5 Interlaken Series 3410 Hydraulic Supply Unit (HSU)

The Series 3410 HSU was supplied with the original Interlaken Load Frame. The Series 3410 Hydraulic Power shown in Figure 25 and Figure 26 consists of a PV6-2L1B-C00 Hagglunds/Denison 20 gpm, 3000 psi variable volume axial piston pump powered by a 41.2 HP, 1800 RPM , T.E.F.C 254 TC frame, 230-460v/3phase/30 hz Baldor electric motor, a water (tube side) to oil (shell side) cooler with a temperature control valve, 30 gallon Joint Industry Council (JIC) reservoir, a pressure relief valve for over pressure protection, which reduces the pump volume to that required by the system while maintaining the preset pressure.

2.2.1.6 Gaertner Traveling Microscopes

The crack growth in the front face, bore and back face were measured using front and back Gaertner model M101A travelling microscopes, mounted to the Interlaken frame by a custom made device shown in Figure 27. The microscopes have a 32x magnification with crosshairs to better visualize the crack endpoint. The Gaertner microscopes allow for eyepieces with various focal lengths depending on the specimen size. For this experiment, the front microscope has the 60 millimeter eyepiece for tracking the front surface crack and the back microscope has the 80 millimeter focal length for tracking bore crack growth.

The Gaertner microscope travel in inches is measured from a zero starting reference point, the edge of the bore hole. This value is displayed on the Fagor Automation digital readout. The tolerance range on the Fagor display is +/-

0.00002 inches, which is well within compliance with the requirement of ASTM E647 of +/-0.004 inches.

The bore crack measurements were taken by placing the back traveling microscope at an angle so the entire bore, from the front face edge to the back face edge, could be seen through the microscope. Then the travel of the microscope, from the front face to the back face, was measured as shown in Figure 28.

The unknown angle can be determined by the relationship of similar triangles and the formula below

$$\theta = \sin^{-1}\left(\frac{Measured\ thickness}{Actual\ thickness}\right) \tag{2.1}$$

Once the angle was known, the traveling microscope was set at zero for the front face and the actual bore crack growth was calculated using the following formula:

$$Bore\ Crack\ Growth = \frac{Measured\ Crack\ Length}{\sin\theta} \tag{2.2}$$

2.2.2 Phase II Testing at Southwest Research Institute (SwRI) Solid and Fracture Mechanics Laboratory

The specimens GT70KB003-11-7, -10, -1, -9 and -27 were all tested on the 100 kip Load Frame as shown in Figure 29 at the SwRI Solid and Fracture Mechanics Laboratory in San Antonio, Texas. The specimen GT70KB003-11-17 was used for the initial fatigue equipment set up and calibration. The specifications for the load frame and the travelling microscopes are shown in Tables 5 and 6, respectively. The specification and background for the hydraulic pump that supplies hydraulic pressure and flow for the 100 kip load frame is shown in Table 7.

2.3 Specimen Preparation

2.3.1 Initial Sanding and Polishing of Specimens

All specimens were manufactured and shipped from Northrop Grumman Technical Services Laboratory with a 125 RHS finish. In order to detect and measure crack propagation, sanding and polishing were performed at the 809 MXSS Science & Engineering Laboratory at Hill Air Force Base. Sanding with 320 grit, then 500 grit, then 800 grit, then 1200 and 2400 grit paper was accomplished to remove the milling marks in the crack propagation direction.

Then polishing was accomplished with electric Struers machine and Struers DP-Dur polishing cloth with 3 micron and then 1 micron diamond paste to produce a mirror finish. All sanding and polishing were performed in the longitudinal direction to prevent nucleation of cracks. The final specimen configuration is shown in Figure 30.

2.3.2 Precracking Phase

All specimens were precracked using the Interlaken Series 3300 55 Kip Fatigue Machine in the 809 MXSS Science & Engineering Laboratory at Hill Air Force Base, shown in Figure 22, according to the loading conditions and geometry requirements specified in ASTM E647. The Spectrum A samples were cycled at 19.5 ksi, representing approximately 70 percent of the maximum spectrum stress at a stress ratio of R=0.05 and a constant amplitude of 6 hertz. The Spectrum B samples were cycled at 16.1 ksi, roughly 70 percent of the maximum spectrum stress at a ratio of R=0.05 and a constant amplitude of 7 hertz. Cycling in all cases was continued until the surface crack length of approximately 0.030 inches to 0.050 inches when the hole was reamed to the final diameter of 0.250 inches.

2.3.3 Final Reaming

The samples were reamed, after precracking, to a final hole diameter of 0.250 inches, using the milling machine in the student machine shop in the Mechanical Engineering Department at the University of Utah. The center of the starter hole was determined by using the dial indicator. Each hole was first drilled with 15/64th drill bit and then reamed with a standard 10 flute, 0.250 inch reamer. The drill operation was performed at 700 rpm and the reaming operation was performed at 80 rpm with lubricant applied. Each specimen was reamed from the back, with the front side having the EDM notch, so that the reamer did not affect the EDM notch.

2.3.4 Final Sanding and Polishing

The edges of the specimens were sanded with 1200 grit paper to reduce surface anomalies and discontinuities that might be sources of crack nucleation. The edge of the hole was de-burred and sanded to remove burrs left from the drilling and reaming process. The surface around the hole and the bore were polished with 3 micron and then 1 micron diamond paste, using the Dremel rotary tool, to allow for better visibility of the crack measurement on the surface and inside the bore.

2.4 Fatigue Testing Procedures

Once the specimens were prepared to the final testing configuration, each specimen was tested according to the following process:

2.4.1 Balancing Load Cell

Before testing of each specimen, the load cell is balanced, similar to the procedure for balancing a lab weight scale to the zero setting. This is accomplished in the Intstron Bluehill2 console software by first placing the controller in position control and in the load software, selecting the Balance button to zero the load.

2.4.2 Loading the Specimen into Load Frame

Once the load cell was balanced, the Specimen Safety button was selected to ensure that the loading would not exceed 100 pounds. The maximum and minimum load limits were set with 10 percent margin, to ensure the specimen would be protected during inadvertent load frame movement during loading and testing. The upper cross head position was adjusted by unlocking the cross arm and adjusting the position of the upper cross head and the lower actuator to allow for full contact of grip and specimen on top and bottom. The lower actuator was set to a starting position that allowed for full movement during the test without exceeding the 3 inch travel limit in the tensile loading direction. Once the position was set, the upper position actuator was locked. The maximum and minimum position were set +/- 0.1 inch from the starting position to prevent inadvertent damage to the specimen during loading and testing. The specimen was carefully loaded to ensure vertical alignment with the frame and confirmed full grip contact to specimen and then locked the upper and lower grips on the Intensifier Console.

2.4.3 Testing Procedure

Once the specimen was loaded, the controller was placed in Load Control and the load was set to zero. The Instron Random Loading software was used to select the Constant Load Rate and enter the desired load rate in lbs/sec. The samples were run at 100,000 lbs/sec and later had to be run at 80,000 lbs/sec to keep the error below 2 percent with the Rexroth pump configuration. With the newly installed Denison pump, the specimens were tested at 150,000 lbs/sec with an error below 2 percent.

Once the appropriate spectrum file was loaded according to the randomized specimen sequence list shown in Table 8, the fatigue testing was initiated by selecting Start Testing on the Instron Random Loading software.

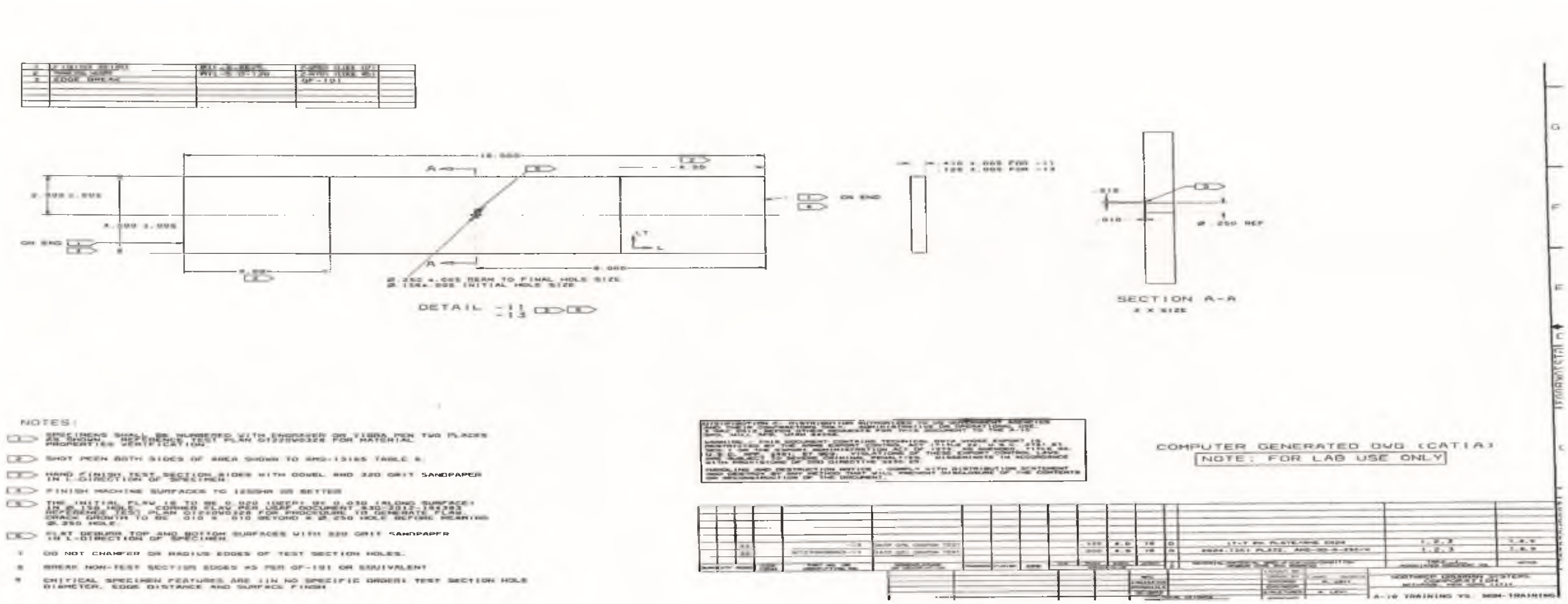


Figure 19 GT70KB003-11 Specimen Drawing

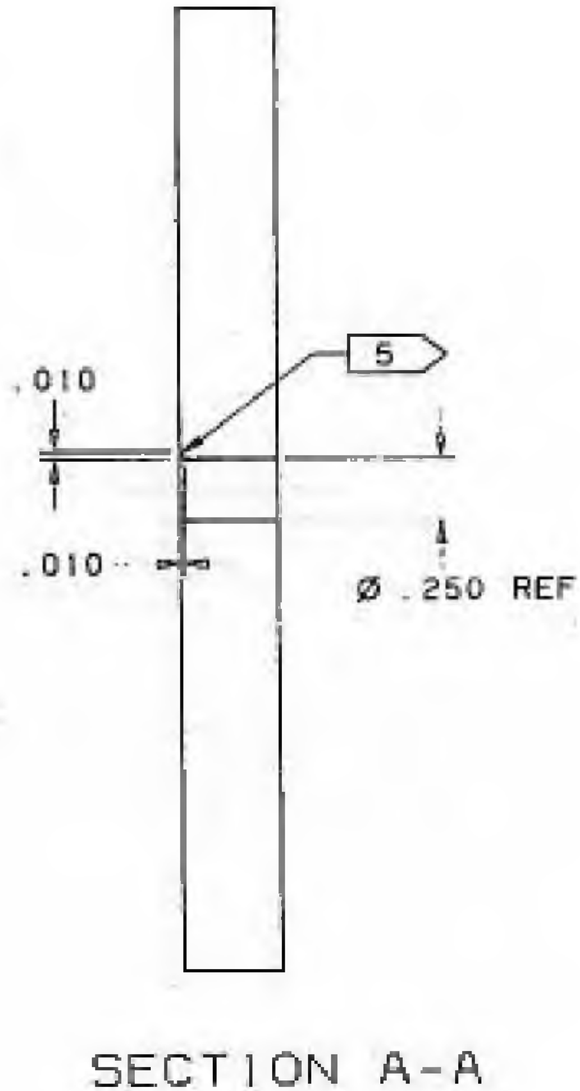


Figure 20 GT70KB003-11 Drawing Cross-Section Detail

NOTES:

1. SPECIMENS SHALL BE NUMBERED WITH ENGRAVER OR VIBRA PEN TWO PLACES AS SHOWN. REFERENCE TEST PLAN GT220W0328 FOR MATERIAL PROPERTIES VERIFICATION.
2. SHOT PEEN BOTH SIDES OF AREA SHOWN TO AMS-13165 TABLE 6.
3. HAND FINISH TEST SECTION SIDES WITH DOVEL AND 320 GRIT SANDPAPER IN L-DIRECTION OF SPECIMEN.
4. FINISH MACHINE SURFACES TO 125RHR OR BETTER
5. THE INITIAL FLAW IS TO BE 0.020 (DEEP) BY 0.030 (ALONG SURFACE) IN Ø.156 HOLE. CORNER FLAW PER USAF DOCUMENT A3G-2012-184363 REFERENCE TEST PLAN GT220W0328 FOR PROCEDURE TO GENERATE FLAW. CRACK GROWTH TO BE .010 X .010 BEYOND A Ø.250 HOLE BEFORE REAMING Ø.250 HOLE.
6. FLAT DEBURR TOP AND BOTTOM SURFACES WITH 320 GRIT SANDPAPER IN L-DIRECTION OF SPECIMEN.
7. DO NOT CHAMFER OR RADIUS EDGES OF TEST SECTION HOLES.
8. BREAK NON-TEST SECTION EDGES AS PER DF-(D) OR EQUIVALENT
9. CRITICAL SPECIMEN FEATURES ARE (IN NO SPECIFIC ORDER) TEST SECTION HOLE DIAMETER, EDGE DISTANCE AND SURFACE FINSH

Figure 21 GT70KB003-11 Drawing Notes

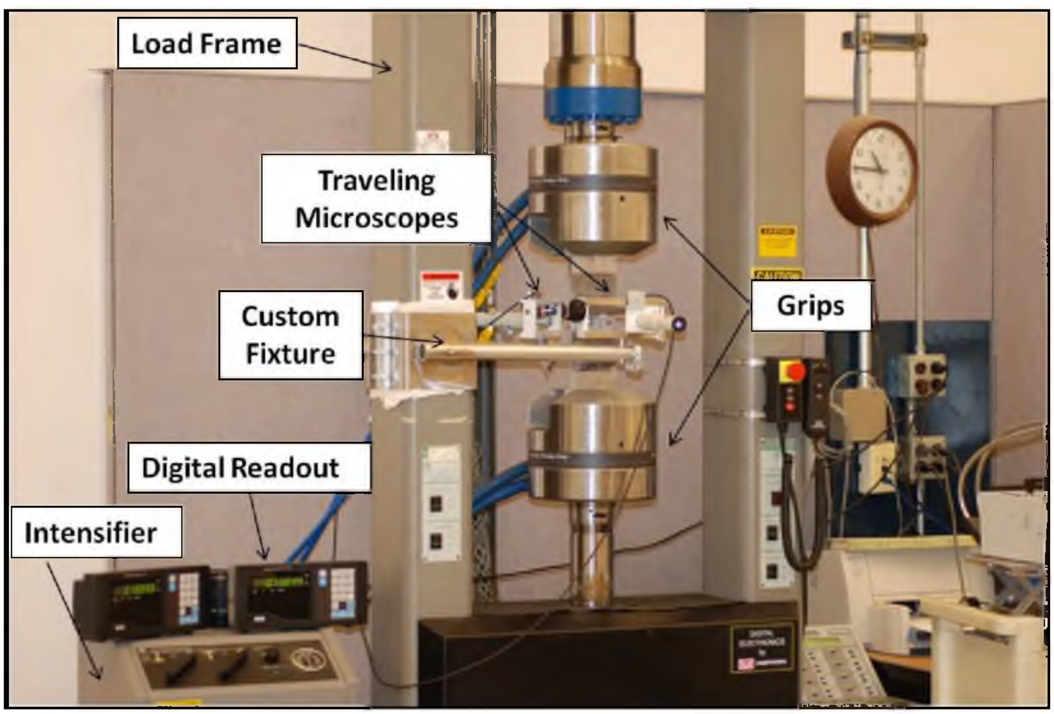


Figure 22 Interlaken Machine with Microscope Custom Fixture[34]

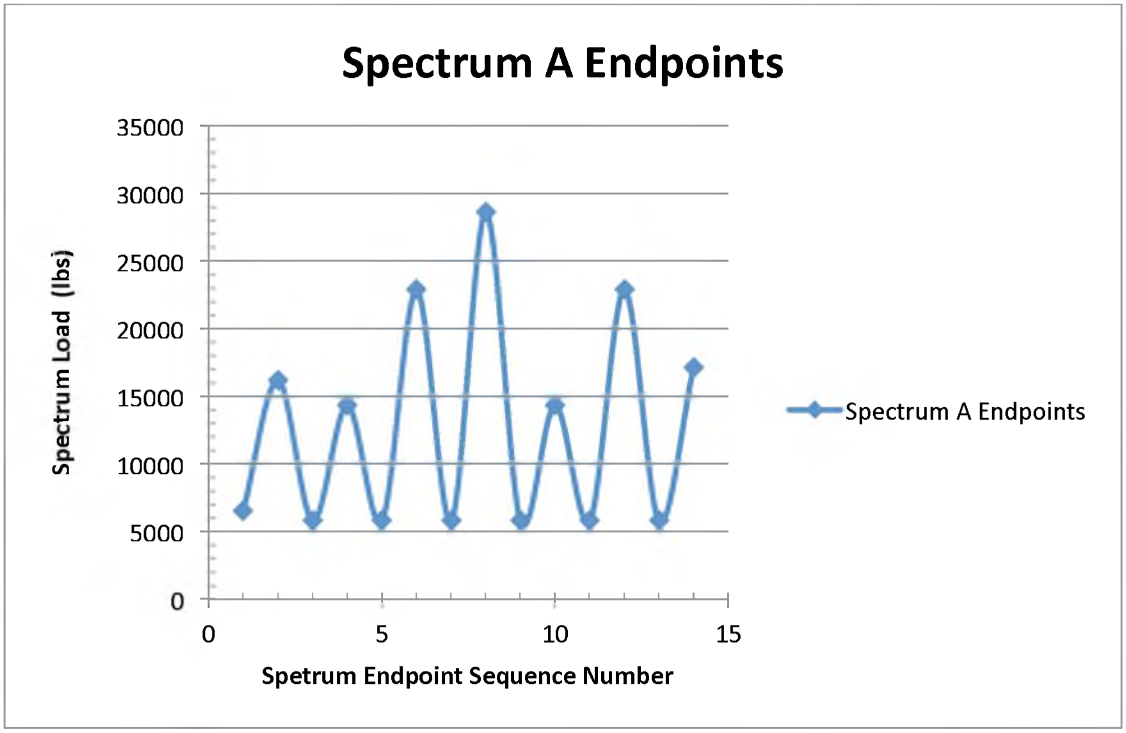


Figure 23 Graphical Depiction of Spectrum A Endpoints

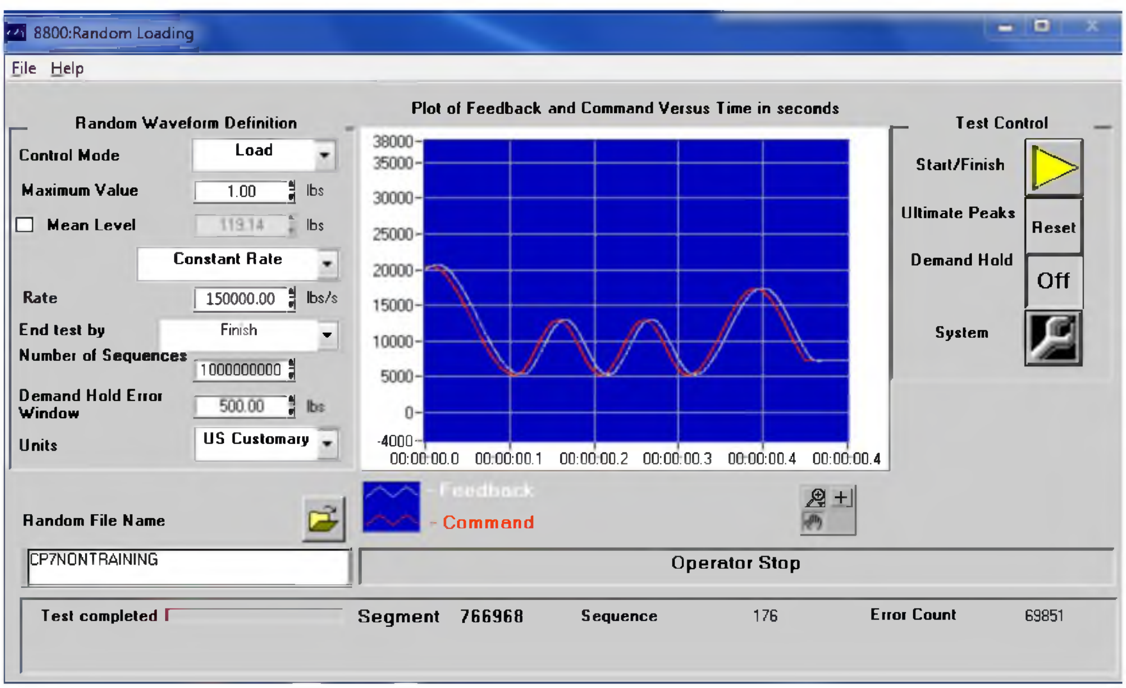


Figure 24 Instron Random Loading Screenshot

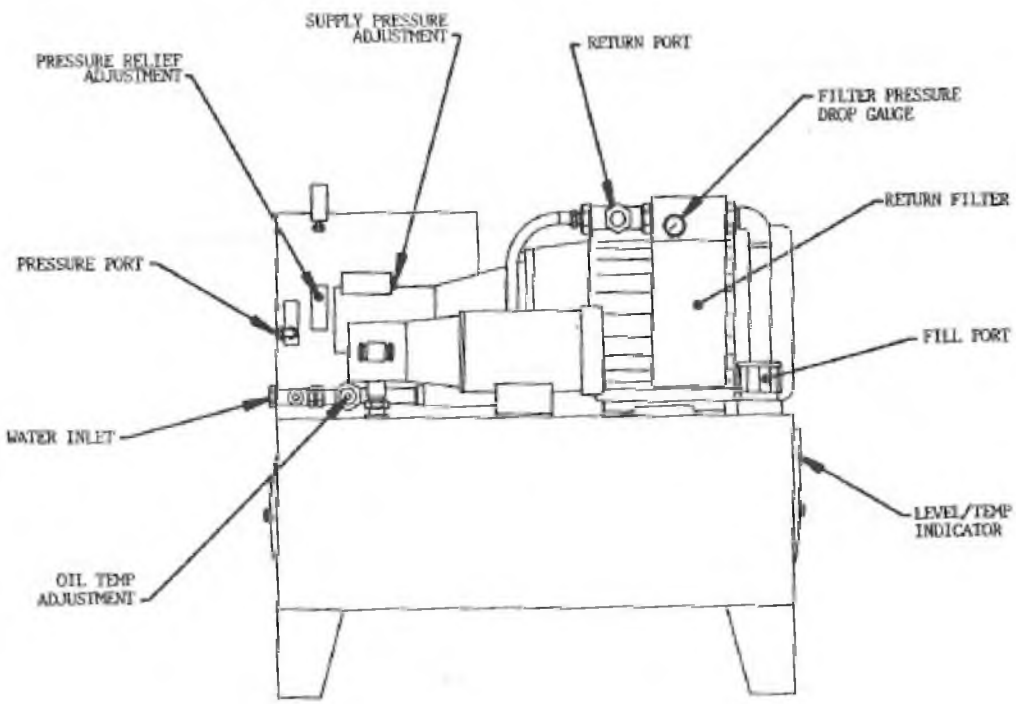


Figure 25 Interlaken Hydraulic Supply Unit Schematic[35]

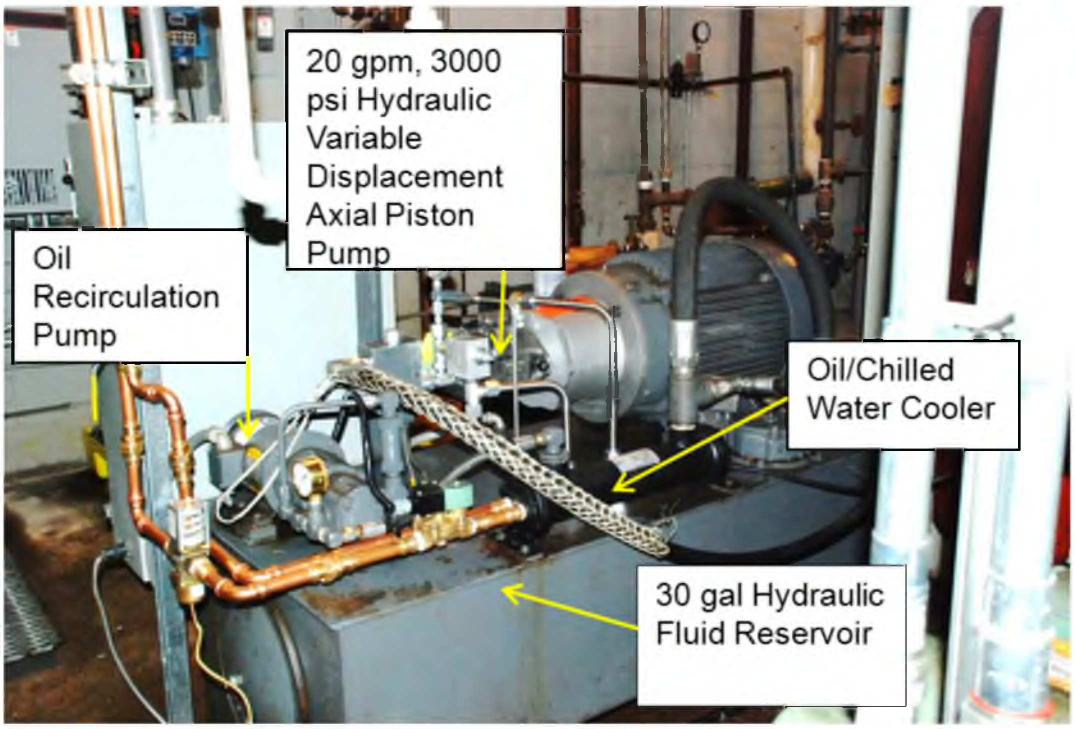


Figure 26 Interlaken HSU in Equipment Room Photo

Figure 27 Gaertner Traveling Microscope

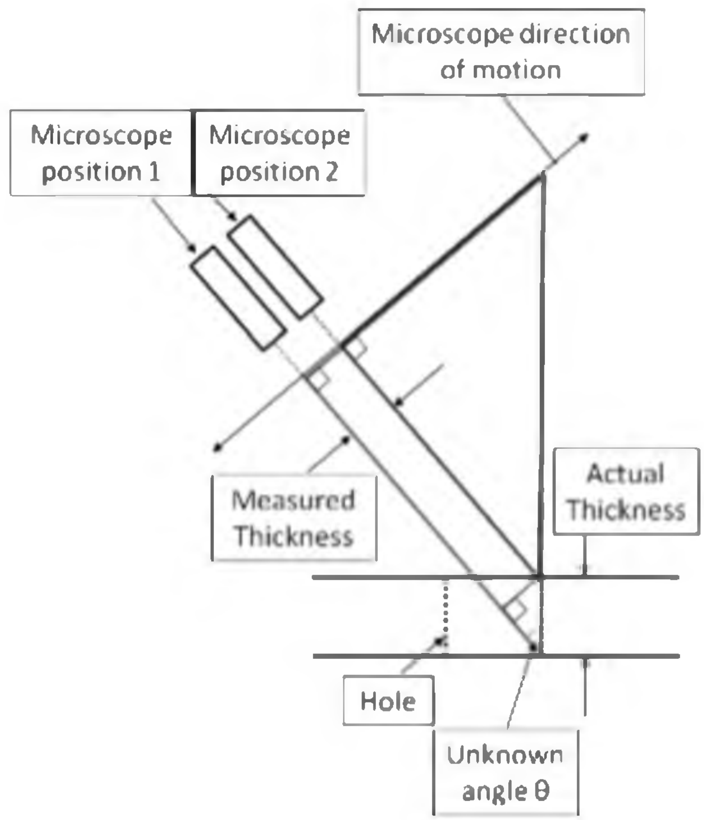


Figure 28 Bore Crack Measuring Process[36]

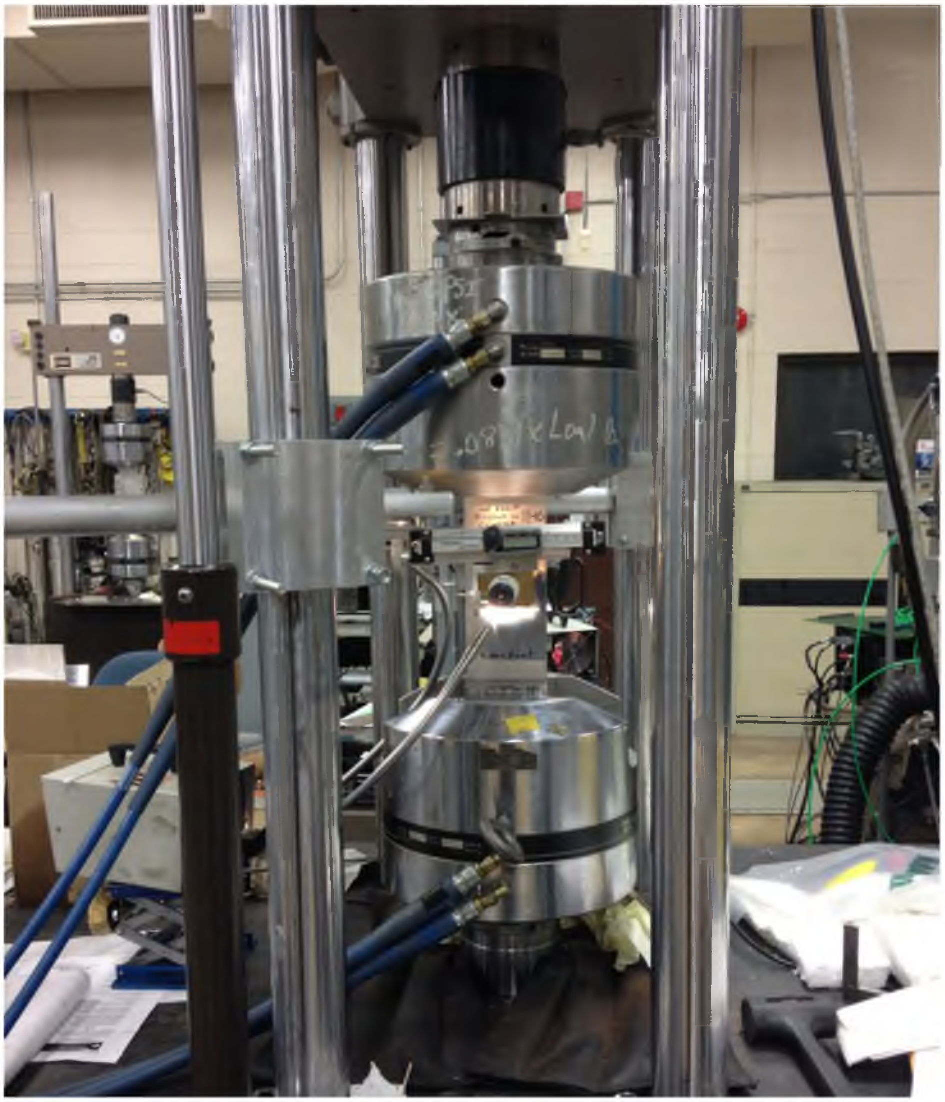


Figure 29 SWRI 100 Kip Load Frame Front View

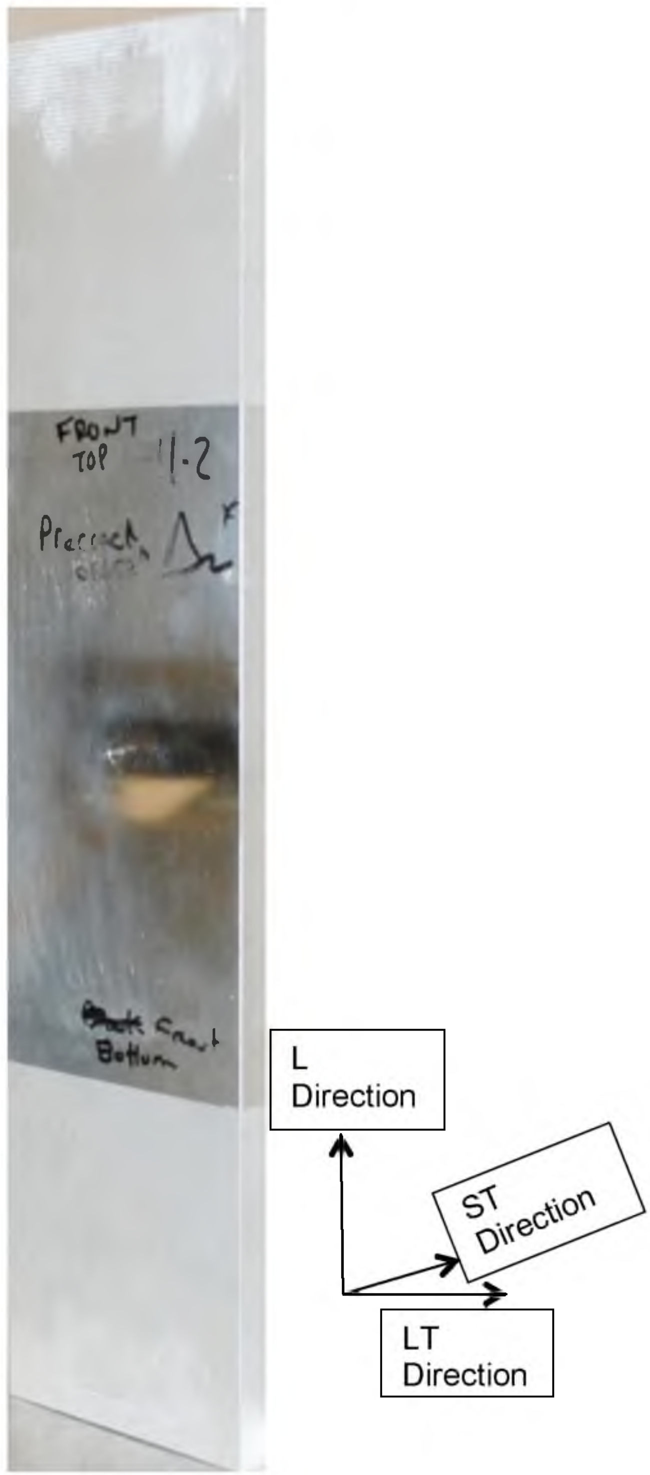


Figure 30 Specimen Grain Direction

Table 2 Aluminum 2024-T351 Alloy Composition

Component	Weight Percentage
Al	90.7 - 94.7
Cr	Max 0.1
Cu	3.8 - 4.9
Fe	Max 0.5
Mg	1.2 - 1.8
Mn	0.3 - 0.
Si	Max 0.5
Ti	Max 0.15
Zn	Max 0.25
Other, each	Max 0.05
Other, total	Max 0.15

Table 3 Spectrum A Load (lbs) Endpoints

6512
16185.6
5787.3
14332.6
5787.3
22878.8
5787.3
28601.6
5787.3
14332.6
5787.3
22878.8
5787.3
17181.2

Table 4 Instron Random Loading Inputs

Random Loading Software Feature	**Explanation**	**Thesis Testing Selection**
Control Mode	Position or Load Control	Load
Maximum Value	Scale or Multiplication Factor applied to loads in input spectrum file	Factor of 1
Mean Level	Adds the load input to a selected mean level instead of zero load	Unselected
Loading Option	Frequency, Constant Load Rate,	Constant Load Rate in lbs/second
End Test	Criteria for terminating test	At the end of 10^9 Sequences
Demand Hold Error Correlates to Demand Hold button on right hand side of menu	Allows for loading to hold until the command value is reached to a certain error level in lbs. This input defines the accuracy of that load value.	Demand Hold - Off
Error Record Input (not shown)	The error between the command and feedback level is calculated for every endpoint and the error value point at which this can be recorded into a file can be input.	Set at zero error in the beginning of each specimen run to assess and record error, then selected to 1% to conserve computer memory space.

Table 5 100 Kip Load Frame Specifications

100 kip Load Frame Information	
Load Size	100 kip
Model #	MTS 322.41S
Serial #	379792
Servo Valve	2 (5 GPM each)
Capacity	100 kip
Load Cell	MTS 661.23E-01
Grips	MTS 100 kip 647.50
FTA version	V3.12.08

Table 6 Traveling Microscope Details

Traveling Microscopes	
Magnifcation Scope	Gaetner Scopes (2 per test frame); 10X eyepiece, 38 mm EFL
Measurement Device	6" Digital Scales (certification provided by SwRI calibration laboratory; annually)
Mounting Hardware	SwRI custom brackets anchored to frame posts

Table 7 Hydraulic Pump Information

Fatigue Machine Hydraulic Pump Information	
Motor	Baldor (2)
HP	100 (each)
Flow Rate	50 GPM (each), 100 GPM total
Pressure	3000 psi
History	Designed and implemented by SwRI staff in the 1980s; not a commercially produced system
Primary Cooling	Refrigerant based heat exchanger (compressor/evaporator)
Secondary Cooling	Air over water heat exchanger (radiator)

Table 8 Randomized Specimen Run Order

Sample	Spectrum	Notes
GT270KB003-11-4	Baseline A	Testing with Rexroth Axial Piston Hydraulic Pump
GT270KB003-11-11	A + B Combo 2	Testing with Rexroth Axial Piston Hydraulic Pump
GT270KB003-11-6	A + B Combo 1	Testing with Rexroth Axial Piston Hydraulic Pump
GT270KB003-11-13	A + B Combo 3	Testing with Rexroth Axial Piston Hydraulic Pump
GT270KB003-11-12	A + B Combo 3	Testing with Rexroth Axial Piston Hydraulic Pump
GT270KB003-11-29	Baseline B	Testing with Rexroth Axial Piston Hydraulic Pump
GT270KB003-11-7	A + B Combo 1	Testing at SWRI Solid & Fracture Mechanics Lab
GT270KB003-11-10	A+ B Combo 2	Testing at SWRI Solid & Fracture Mechanics Lab
GT270KB003-11-1	Baseline A	Testing at SWRI Solid & Fracture Mechanics Lab
GT270KB003-11-9	A + B Combo 3	Testing at SWRI Solid & Fracture Mechanics Lab
GT270KB003-11-27	Baseline B	Testing at SWRI Solid & Fracture Mechanics Lab
GT270KB003-11-5	Baseline A	Testing with Denison Axial Piston Hydraulic Pump
GT270KB003-11-8	A + B Combo 2	Testing with Denison Axial Piston Hydraulic Pump
GT270KB003-11-3	A + B Combo 1	Testing with Denison Axial Piston Hydraulic Pump
GT270KB003-11-28	Baseline B	Testing with Denison Axial Piston Hydraulic Pump
GT270KB003-11-2		Spare
GT270KB003-11-17		SWRI initial Equipment Setup Coupon
GT270KB003-11-30	Baseline A	Repeat run to replace Sample 4
GT270KB003-11-31	A + B Combo 2	Repeat run to replace Sample 11
GT270KB003-11-32		Spare
GT270KB003-11-33		Spare

CHAPTER 3

FATIGUE TESTING DATA COLLECTION AND PROCESSING

3.1 Visual Crack Measurements

Using the front Gaertner Traveling Microscope, the starting position for the front face was set at the edge of the bore hole and the Fagor Readout display was set to zero. The back Gaertner Traveling Microscope was set at an angle to view the entire bore and the telescope angle was calculated using the procedure outlined in section 2.2.1.6. The back Microscope was set at the starting position of the front face bore edge and the Fagor Readout display was set to zero. The front face and bore crack lengths from the Precrack and Final Reaming Phases were measured and recorded before testing began.

Measurements on the front face and bore were taken at regular intervals and the corresponding endpoint count from the Instron Random Loading Software was recorded. The segment count was converted to Effective Flight Hours using the formula in Table 9 according to the specimen spectrum combination.

3.2 Error Calculation and Analysis

The error recording level was initially set to zero percent so that the command and feedback load and corresponding error between the two was recorded for every endpoint. The error was calculated according to the following formula:

$$Error\,(\%) = \frac{Command\ Load - Feeback\ Load}{Command\ Load} \qquad 3.1$$

This error recording level was maintained for at least two sequences so that an average error could be calculated. If the error exceeded 2 percent, then the Constant Load Rate was adjusted to a lower rate and the process was repeated until the average error was below 2 percent. Once achieved, the error record level was re-set to 1 percent to prevent using up computer memory.

3.3 Baseline Spectrum Testing

The baseline Spectrum A and B specimens were tested by loading the corresponding spectrum and running the fatigue test until full fracture occurred.

3.4 Spectrum Combination Testing

The A + B Combination 1 , A + B Combination 2, A + B Combination 3 specimens were testing with the Spectrum A loading file until the appropriate switch point in the bore was reached, at which point the Spectrum B load file was selected. These spectrum switch points are shown in Figure 18. The A + B Combinations were only run for 100,000 EFH flight hours during the B portion to model the crack growth during the interval between depot level inspections.

3.5 Determining Retardation Effect Using AFGROW

The Air Force Grow (AFGROW) software program, developed by the Air Force Research Laboratory, was used to model the Aluminum 2024-T351 alloy response to the spectrum loading using the Willenborg Retardation Model. This was accomplished by adjusting the values for the Shutoff Overload Ratio (SOLR) to achieve AFGROW-generated fatigue crack growth curve to fit the actual fatigue crack growth curve from the experiment.

3.5.1 Specimen Model Geometry

There were two AFGROW models used to model the retardation effect of the spectrum loading.

3.5.1.1 Baseline Spectrum and AB Combination Specimen Model Geometry

For the Baseline A&B data and the AB Combo. 1 and AB Combo. 2, the Single Corner Crack at Hole model was used. This AFGROW geometry model is based on stress intensity equations developed by Newman and Raju using the quarter-Elliptical Corner Crack geometry as depicted in Figure 31.[37]

The 2D profile of the part thickness with the hole and corner crack detail shown in Figure 32 is the same as that in the AFGROW Geometry input software window. Figure 33 shows the 3 coordinate systems for the corner crack to define the parametric Newman-Raju equation for aspect ratios greater than and less than 1. For all specimens, which represent the combinations in this experiment, the starting aspect ratio was greater than 1.

The measured coupon aspect ratio was input for each AB combination. Figure 34 shows the various geometry inputs to conduct the AFGROW analysis. Figure 35 shows the Dimension input screen used for the Single Corner Crack at Hole model for the Baseline A and B retardation modeling.

The AFGROW modeling initial configuration was based on the measured aspect ratios from the coupon data and is shown in Figure 36 for Spectrum AB Combo 1 and in Figure 37 for Spectrum AB combo 2. The Spectrum AB Combo 1 starting crack profile were the measured bore crack and front crack values from the coupon data, with the target switch point bore crack at 0.20 inches and the corresponding front face crack at 0.12 inches. The Spectrum AB Combo 2 inputs were the measured bore and front crack values of 0.328 inches and 0.218 inches. The SOLR values were adjusted for the best AFGROW fatigue crack curve to fit the coupon crack growth data.

3.5.1.2 Spectrum AB Combination 3 Specimen Model Geometry

The AB Combination 3 specimens were modeled in AFGROW using the Oblique Through Thickness Crack in Hole geometric feature. This calculation is based on the stress intensities developed by S.A. Fawaz using an elliptical crack front as shown in Figure 38.

For the AB Combo 3 crack modeling, the Oblique Through Thickness Crack at Hole model was used. Figure 39 shows the user input screen for this model. The inputs included the crack length for the front, C, and the crack length for the back surface, Ct.

An alternative method was used to model the AB Combo 3 crack growth using the actual front crack value from the test and the starting bore crack length as .4099 inches, slightly below the model thickness required by the AFGROW software, but essentially the thickness value, and utilizing the Single Corner Crack at Hole model.

3.5.2 Specimen Model Loads

The AFGROW model loads were read from the same spectrum input file that was used for the fatigue crack growth testing for the Spectrum A and B baseline tests. The AB Combo 1,2, and 3 modeling was accomplished by putting in the crack data for the bore and front crack data (back crack data for AB Combo 3) from the actual test as the starting crack size and using the Spectrum B input load file used during the fatigue test as the load input.

3.5.3 Retardation Models

AFGROW has several options for modeling fatigue crack growth retardation such as the Wheeler, Hsu, Willenborg, Crack Closure Model and NASGRO. The Willenborg model has been used for 2024-T351 material modeling for similar features experiencing tension dominated spectra and was chosen as the model for this experiment. The Willenborg model uses the SOLR parameter as the input variable as shown in Figure 40 for retardation modeling.

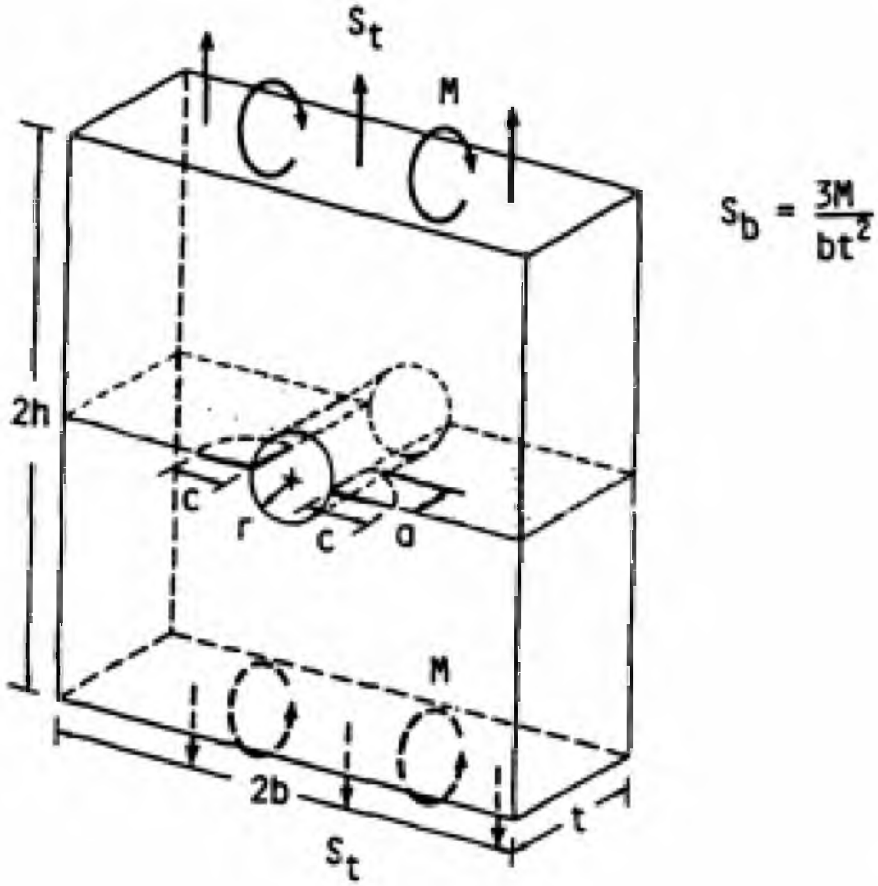


Figure 31 Quarter-Elliptical Corner Crack Geometry

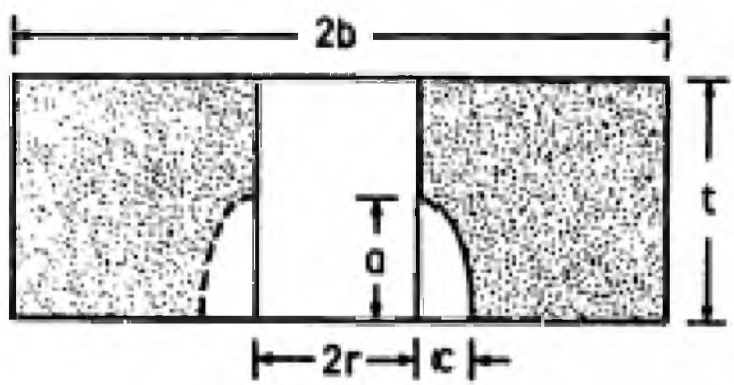


Figure 32 Corner Crack in Hole[38]

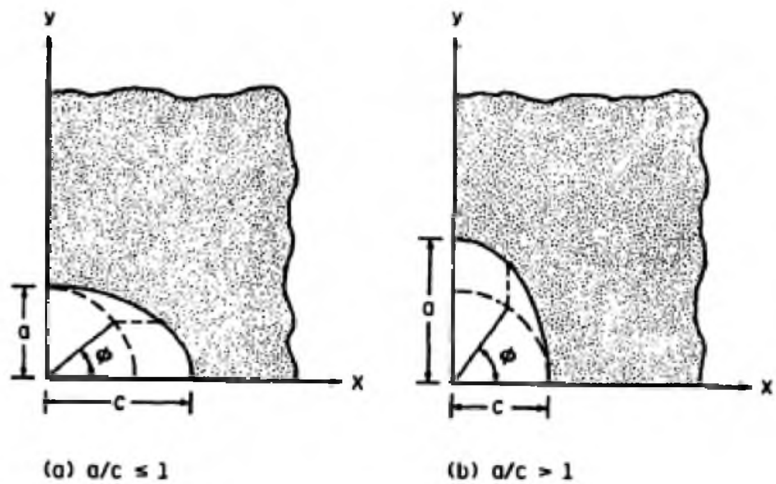


Figure 33 Newman-Raju Aspect Ratios[39]

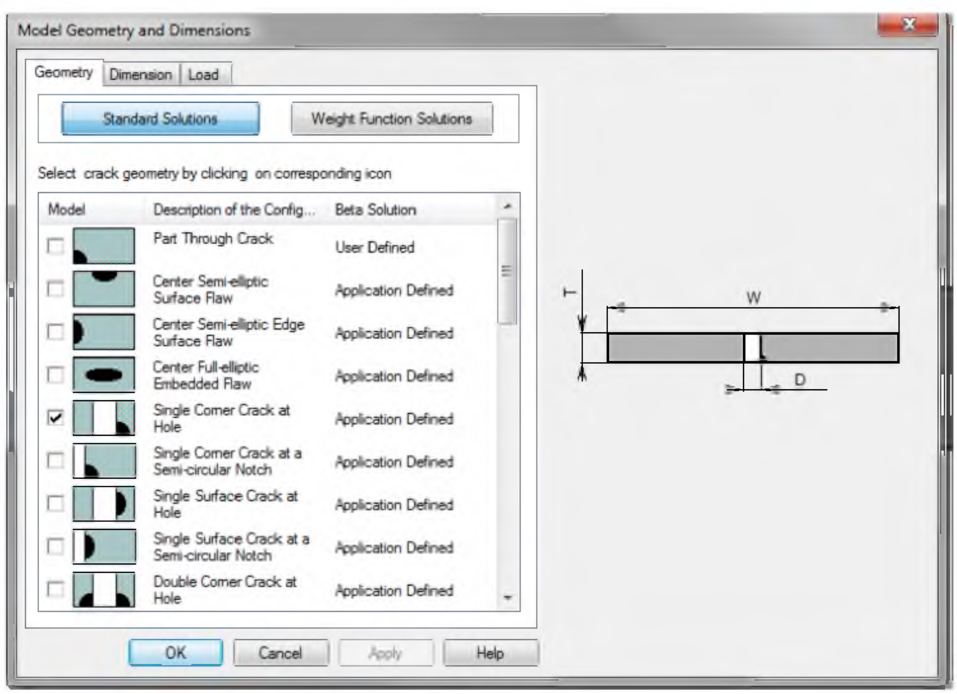


Figure 34 AFGROW Geometry Inputs

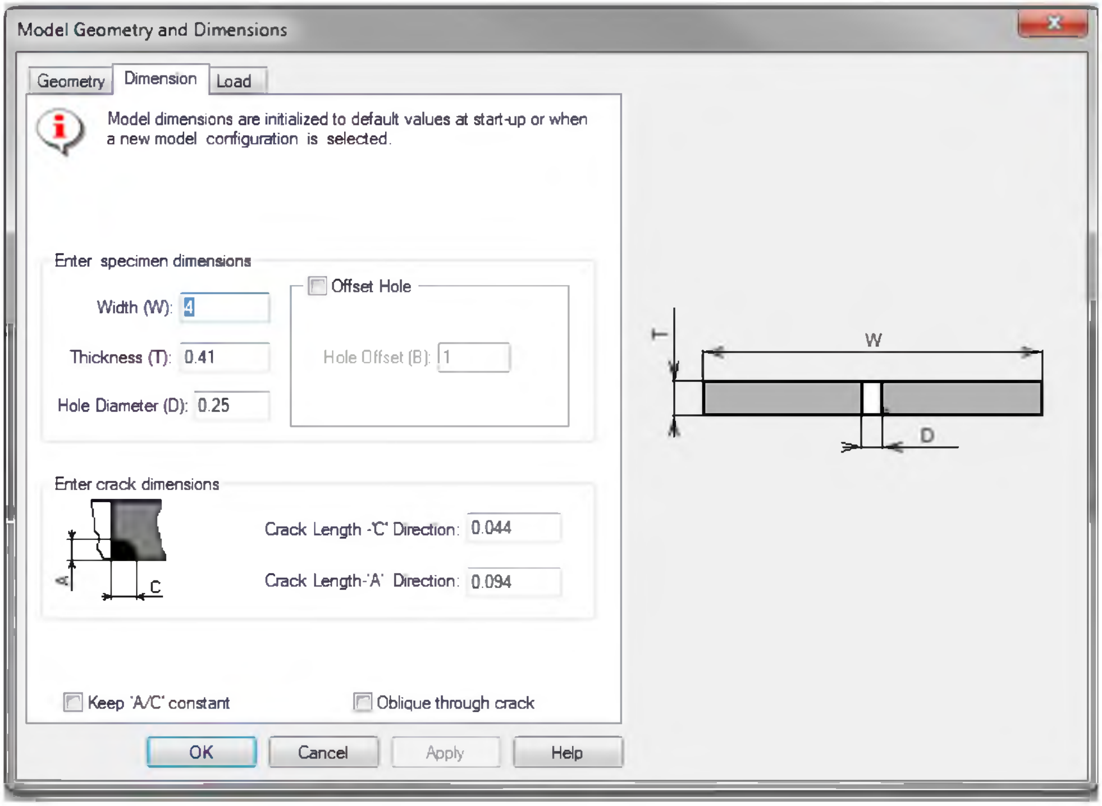


Figure 35 Single Corner Crack in Hole Dimension Screen

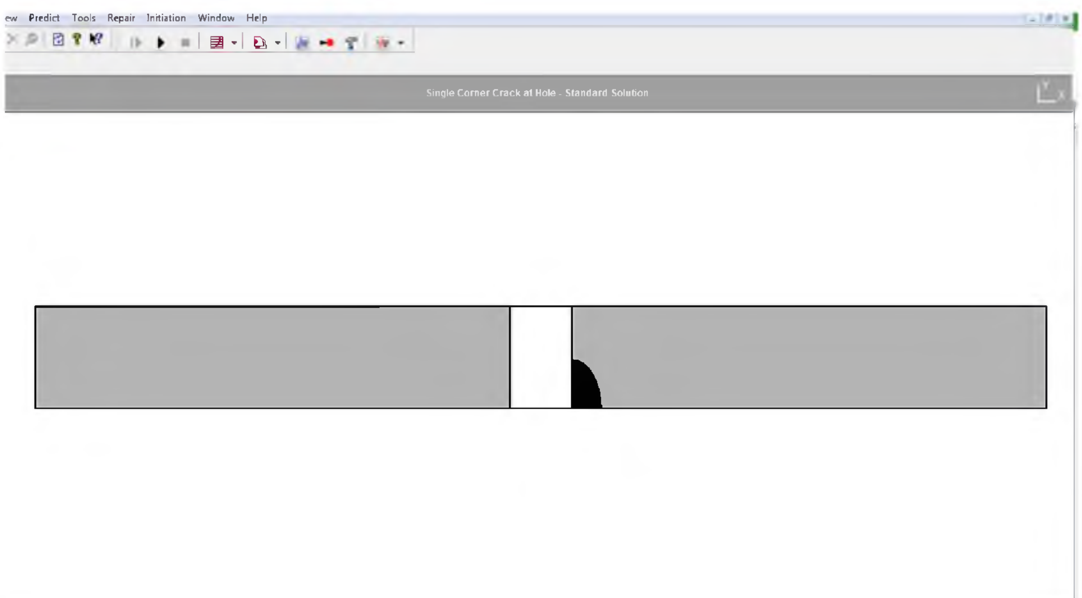


Figure 36 Spectrum AB Combo 1 at .20” Bore Crack Switchpoint

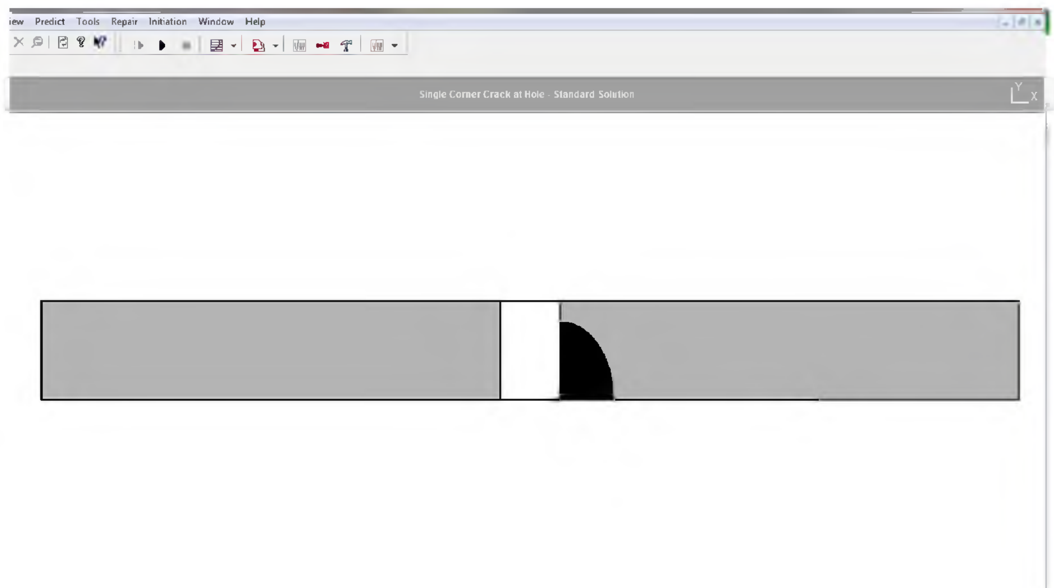


Figure 37 Spectrum AB Combo 2 at 80% Thickness

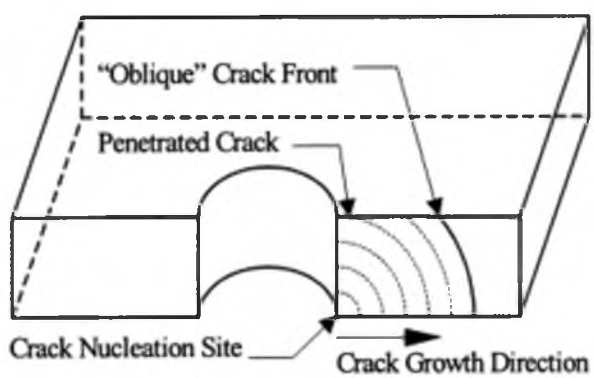


Figure 38 Fawaz Oblique Through Thickness Crack in Hole[40]

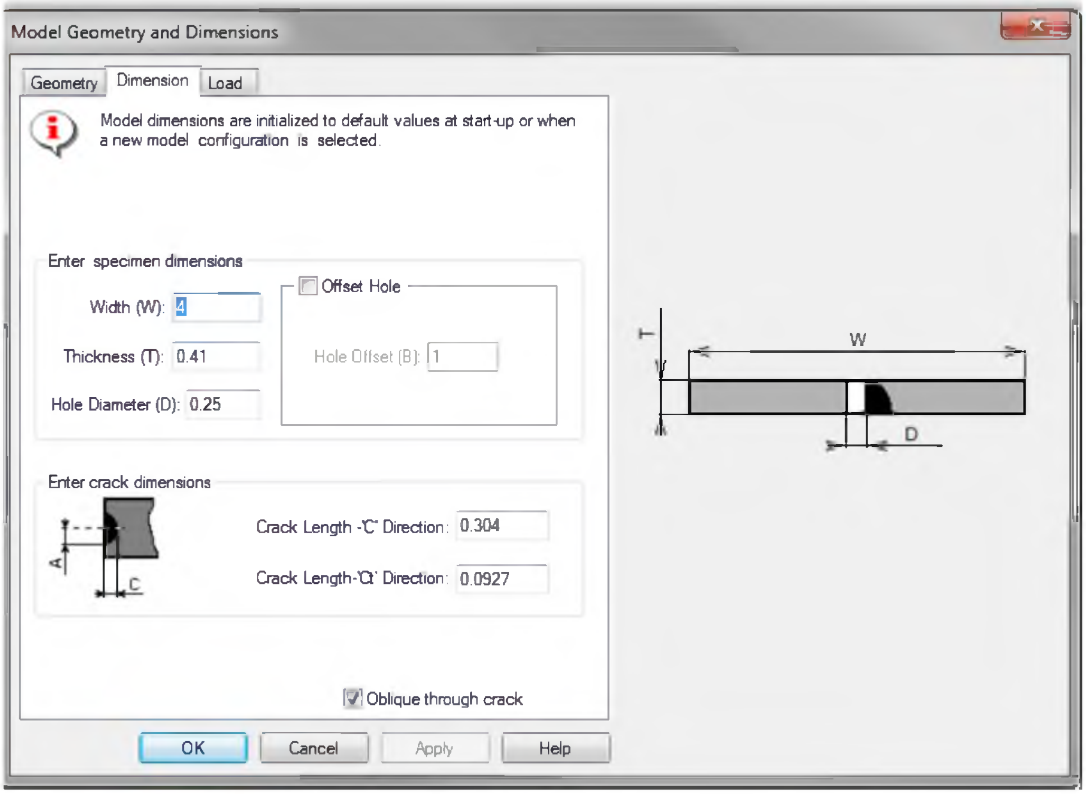


Figure 39 AFGROW Oblique Through Crack in Hole Input

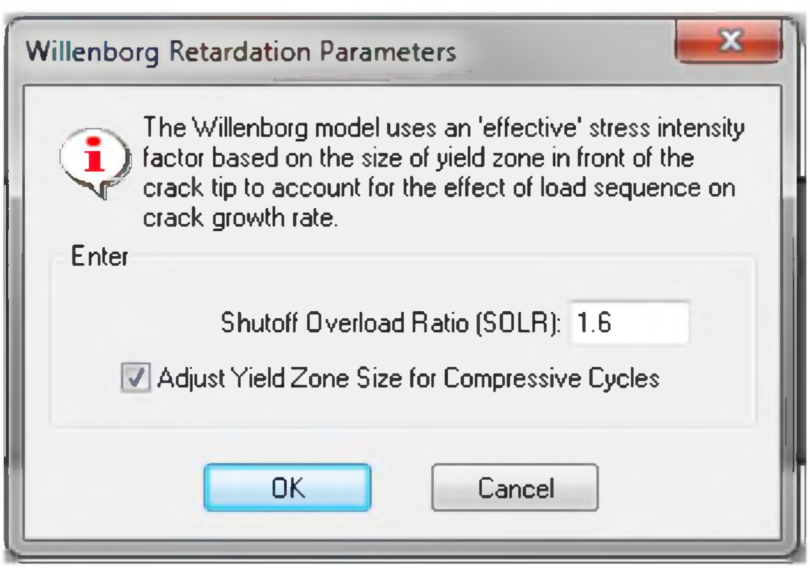


Figure 40 AFGROW Willenborg Retardation Parameter Screen

Table 9 Effective Flight Hours

Spectrum	EFH
A	EFH = # of Segments *240 hours/14737 endpoints
B	EFH = # of Segments *1000 hours/4373 endpoints

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Fatigue Crack Growth Testing

There were 5 unique spectrum combinations for this research with 3 replicates for each combination for a total of 15 specimens. A summary of the 5 combinations is included in Table 10. Two specimens from this group were tested under conditions outside of the test scope and therefore were repeated for each of them. The testing matrix outlining each fatigue test for this research program is outlined in Table 11. The data from the two outlier specimens is useful for comparison and is included in the data graphs. A data sheet for each specimen was maintained with pertinent information to include cross sectional area, diameter, crack growth data, maximum stress, etc. An example of this data sheet is included in Figure 41.

4.1.1 Fatigue Crack Growth Testing Observations

The responses to the spectrum loading are described in this section. In addition to tracking the crack propagation, more qualitative observations were made to include the observation of the plastic zone during the fatigue testing especially when the “overload” endpoints were hit. Through the travelling microscope, the crack growth pattern followed a more tortuous path in relation to the horizontal than expected which differed from the crack growth of the 17-7 PH material tested in a similar program. There was also debris visible without the aid of the microscope emanating from the crack front. There was an audible sound when the specimen was under compressive loading especially during the Spectrum B loading which has the highest compressive underload values.

During fatigue testing for this thesis work, the original pump output flow decreased while the 3000 psi pressure was maintained with +0/-1000 psi fluctuations. This greatly impacted the ability of the fatigue machine to provide an accurate tensile load when commanded. The error between command and feedback was in excess of 2 percent. This was due to inadequate flow required to move the actuator during peak loads. The first two samples were tested at a maximum of 300,000 lbs/sec which magnified the flow problems due to the faulty hydraulic pump and resulted in errors in excess of 3 percent. This effect is shown on the Instron 8800 Fast Track Controller Loop Tuning Tool screenshot shown in Figure 42 in which the cycle speed was 1.5 hertz. In this figure, the red cyclical curve is the desired load commanded by the controller and the green curve is the actual feedback load signal from the load cell. In this instance, the feedback load matched the command curve until approximately the 37 kip point where the hydraulic fluid flow was insufficient to move the actuator to reach the peak load of 45 kips in step with the cycle time.

While a replacement pump was on order, the remaining samples were shipped to Southwest Research Institute (SwRI) Solid and Fracture Mechanics Laboratory and were tested on the equipment described in section 2.3.2. The replacement pump for the Hill AFB Lab HSU, the Denison PVT20, 20 gpm, 3000 psi axial piston, variable displacement open loop pump, was installed in Jan 2014. The remaining specimens were shipped from the SWRI Solid and Fracture Mechanics Laboratory back to Hill AFB and were tested using the Interlaken Series 3300 55 Kip Load Frame described in section 2.3.1.1. The new pump operated according to manufacturer's specifications and the error between command and feedback was maintained below 2 percent.

4.2 Crack Length Versus Effective Flight Hour Plots (a Versus t)

4.2.1 Baseline Spectrum A Specimens

The fatigue crack growth curves for the Baseline Spectrum A specimens in Figure 43 show a marked deviation from specimen GT270KB003-11-4 to the remaining samples with a fracture life of 22,000 EFH and average of 31,000 EFH for the remaining samples. The crack growth data curve from specimen GT270KB003-11- 5 sample tested at Hill AFB with the reconfigured pump matched the crack growth curve corresponding with specimen 1 tested at SWRI. The crack growth for sample GT270KB003-11-30 shows slightly longer fatigue life at 32,000 EFH but this curve shows a deviation at the midway point from that of Samples GT270KB003-11-1 and GT270KB003-11- 5 which corresponds to the exact point when the HSU experienced repeated overheating and subsequent electrical shutdowns terminating the fatigue test.

4.2.1.1 Specimen GT270KB003-11-4

The Baseline Spectrum A specimen GT270KB003-11-4 was tested on the Hill AFB Lab 55 kip fatigue machine at 300,000 lbs/second, which is approximately a frequency of 12 hz, during the period that the 20 gpm Rexroth hydraulic flow performance degraded which resulted in error between the command and feedback load in excess of 3 percent. This effect was more pronounced during the peak loads which resulted in reduction on fatigue growth life.

4.2.1.2 Specimen GT270KB003-11-1

The Baseline Spectrum A specimen GT270KB003-11-1 was fatigue tested at the Southwest Research Institute Solid and Fracture Mechanics Lab using the 55 kip machine at a constant load rate of 100,000 lbs/second, roughly an average frequency of 4 hz.

4.2.1.3 Specimen GT270KB003-11-5

The Baseline Spectrum A specimen GT270KB003-11-5 was fatigue tested after the pump was replaced. With the new hydraulic pump, the flow was consistent and adequate to meet peak load flow demands. This test was accomplished with a constant load rate of 100,000 lbs/second (roughly 4 hz) with the average error between command and feedback load under 2 percent.

4.2.1.4 Specimen GT270KB003-11-31

The Baseline Spectrum A specimen -31 was tested as a replacement specimen for -4 due to the pump problems outlined earlier. During the halfway point of this experiment, excessive temperature in the hydraulic fluid resulted in shutdown stopping the test. The temperature limit was reached approximately every 2 hours causing frequent inadvertent shut down. During a power loss and restart, the controller is no longer operating under the spectrum file and uncommanded loads are likely. If the uncommanded loads are peak loads then this will increase the retardation affecting the crack growth response.

4.2.2 Baseline Spectrum B Specimens

The crack growth curve data corresponding to Spectrum B in Figure 44 show a significant increase in fatigue life over that of Spectrum A, from 31,000 EFH to 540,000 EFH, a 16 fold increase. The crack growth curves for all three samples were in agreement.

4.2.3 Spectrum A + B Combination 1 Specimens

The A+B Combination 1 crack growth curves in Figure 45 follow the Spectrum A Baseline Crack Growth Curve until the 0.20 inch bore crack switch point corresponding to, on average, 8,000 EFH. From this transition point, where the A+B Combination specimens were loading under Spectrum B loading, the curve follows an almost horizontal path until the 60,000 EFH life point where it follows the Spectrum B Baseline crack growth curve. The intent was to assess if the component would have remaining residual strength for 100,000 EFHs under Spectrum B loading.

4.2.4 Spectrum A + B Combination 2 Specimens

The A+B Combination 2 crack growth curves in Figure 46 follow the Spectrum A Baseline fatigue crack growth curve shape until the .80*thickness switch point to the Spectrum B loading. From this transition point, at 19,000 EFH, the crack growth curve is horizontal until 80,000 EFH, a delta of 61,000

EFH, at which point, the curve matches that of the Spectrum B Baseline. The specimen 11 tested at Hill AFB with the faulty pump is included for comparison. The specimens that were tested at Hill AFB with the replacement pump correlated with those tested at SWRI.

4.2.5 Spectrum A + B Combination 3 Specimens

The A+B Combination 3 crack curves in Figure 47 follow the Spectrum A fatigue crack growth curve until the through thickness switch point at 21,000 EFH. For this A+B combination, the curve is horizontal until 45,000 EFH with a delta EFH of 23,000 EFH versus 52,000 EFH and 61,000 EFH for Combination A+B 1 and Combination A+B, respectively. The fatigue growth curves for all specimens correlate well. The fatigue test for specimen 9 was conducted until full fatigue fracture was achieved for a fatigue life of 220,000 EFH.

4.3 AFGROW SOLR Plots vs. Specimen Crack Growth Plots

The AFGROW-generated fatigue crack growth curves, using the Generalized Willenborg Retardation SOLR input until a best fit was obtained, correlated well with the measured fatigue crack growth data from the Baseline Spectrum A and B specimens. This is represented in Figure 48 for Baseline Spectrum A and Figure 49 for Baseline Spectrum B. The Spectrum A+B Combination 1 and 2 crack growth curves generated from AFGROW showed agreement, although not as exact as that seen for the Baseline A and B AFGROW curves. The Spectrum A+B Combination 3 curve provided the closest fit to the measured data from those specimens. Previous attempts to develop an AFGROW curve to shift that curve to the right, by using SOLR values with higher retardation, i.e., lower SOLR value, moved the curve beyond the measured data. The curve shown is the best fit and matched the end of life. Since the measured crack growth data curve for the A+B Combination is really a compound curve with one section showing little to no growth due to retardation to a certain point, and then a curve in the shape of the AFGROW model, further development of AFGROW modeling to develop compound shapes based on multiple input blocks would be beneficial.

The Spectrum A+B Combination 3 presents an interesting modeling scenario where the bore crack transitions through the thickness. This was calculated using two geometric models. The first was developed by Newman and Raju for a single corner crack growing through the bore with a length just 0.0001 inches less than the through thickness. The other was developed by Fawaz based on an oblique crack front with some back face growth after the crack has grown through the thickness. Both crack growth models lined up with each other but have different SOLR values.

Luciano “Lucky” Smith, lead analyst at Southwest Research Institute, speaks to this scenario as follows: [41]

> The AFGROW classic solutions for corner cracked holes in tension are all determined using Newman-Raju stress intensities. It seems appropriate therefore to be able to use any of them – as measured or constant aspect ratio – for correlation since they all were calculated using the same methodology. The same cannot be said for the through crack stress intensities. The straight and oblique crack solutions were developed separately by different researchers, and can give significantly different stress intensities for very similar crack fronts. The use of one for correlation and the other for final analysis could possibly lead to inappropriate SOLR values. The most accurate method for determining stress intensities may therefore be the use of as measured crack lengths and depths for the corner crack portion of growth and a straight crack

once it transitions through the thickness.

Since the AFGROW Geometric Function, Oblique Through Thickness Crack, mirrored the actual crack front shape seen in the fractography work and the SOLR value is more conservative, this approach was utilized.

4.3.1 Baseline Spectrum A Specimen AFGROW SOLR Plots

The AFGROW generated fatigue crack growth curves, using the Generalized Willenborg Retardation SOLR input until the best fit to the measured data was obtained. This best fit SOLR is 1.6.

4.3.2 Baseline Spectrum B Specimen AFGROW SOLR Plots

The AFGROW generated fatigue crack growth curves, using the Generalized Willenborg Retardation SOLR input until the best fit to the measured data from the Baseline Spectrum B loading was obtained. This best fit SOLR is 1.75.

4.3.3 Spectrum A + B Combination 1 Specimens AFGROW SOLR Plots

The AFGROW generated fatigue crack growth curves in Figure 50, using the Generalized Willenborg Retardation SOLR input until the best fit to the measured data from the Spectrum A+B Combination 1 loading was obtained. This best fit SOLR is 1.65.

4.3.4 Spectrum A + B Combination 2 Specimens AFGROW SOLR Plots

The AFGROW generated fatigue crack growth curves in Figure 51, using the Generalized Willenborg Retardation SOLR input until the best fit to the measured data from the Spectrum A+B Combination 2 loading was obtained.

4.3.5 Spectrum A + B Combination 3 Specimens AFGROW SOLR Plots

The AFGROW program was used according to the process described in section 3.3.1 to model the crack growth using the Oblique Through Crack in Hole geometric model. This matched the observed switch point for each of the AB Combo 3 specimens since it was difficult to switch to the B Spectrum at the exact moment the bore crack reached the through thickness point. The crack growth front is in an elliptical 2D form and the microscope can only pick up the surface crack growth. Even if there is no visible surface crack growth through the microscope, the crack front has progressed just under the surface on the back face. Quickly, crack growth on the back surface goes from zero to .09 inches.

The through thickness crack front oblique shape is exaggerated at the switch point and the shape becomes more uniform as the crack progresses. At the final fracture point the shape is still not completely uniform as depicted in the photo in Figure 52 and the AFGROW final fracture picture in Figure 53.

The plot of the AFGROW Oblique Through Thickness Crack in Hole model of the AB Combo 3 is shown in Figure 54. The SOLR value was adjusted in the Willenborg Retardation Model for the best fit with the observed coupon data. The SOLR value of 1.80 was the best fit.

The alternative AFGROW method of setting the bore crack length at just under the part thickness, .40999 inches, a requirement of the AFGROW software to be under the part thickness, was also accomplished using the Single Corner Crack in Hole Feature and is shown with the Oblique Crack AFGROW method in

Figure 55. The fatigue crack curve lies right on top of the Oblique Crack Curve but the retardation value SOLR is 1.64.

4.4 Aspect Ratio Data

Since the stress intensity models used by Newman-Raju for a single quarter-elliptical crack in a hole geometry are dependent on the crack aspect ratio a/c, these data were captured and shown graphically in Figures 56-60 for easier display. In all instances, the starting crack aspect ratio was greater than 1 and in most cases greater than 2 and as high as 3. In all instances, the aspect ratio dropped as the crack grew down the bore with a final aspect ratio of, on average, 1.2 to 1.4. Since the stress concentration is the greatest at the hole and remains constant throughout the bore length or part thickness, and the front crack is the smallest, it is expected for the aspect ratio to be the highest at the beginning of the experiment. However, as the front crack grows the front crack stress intensity increases lowering the aspect ratio value.

4.5 Inspection Interval Update

For comparison, an aircraft under the Spectrum A loading scenario, by Air Force standards for fatigue critical structure, could have an inspection interval at one quarter of the fatigue life, or 0.25*(31,000 EFH) which is 7750 EFHs. This would represent the current situation.

The increase in fatigue life for the Spectrum B Baseline specimens was 16 times that for the Spectrum A Baseline specimens, which should in turn increase the inspection interval by 16*(7750 EFH) which is 124,000 EFH. So, if the inspection interval, for a newly manufactured component, was developed using the Spectrum B Baseline as opposed to remaining with analysis based on Spectrum A, there would be significant economic benefit while maintaining the same level of safety.

The Spectrum A + B combinations, except for the specimen 9 Combination 3 type, were not run to full fracture as designed by experiment goals so the actual life increase was not obtained. However, in all instances, the specimen fatigue crack growth data showed that at the 100,000 EFH point, there was sufficient remaining residual fatigue life based on the crack growth length compared to the critical crack size on other specimens. This demonstrates that if a temporary change to spectrum B were to occur, maintenance intervals could be relaxed temporarily with confidence knowing there would be no near term impact on flight safety. This relaxation would not be on the order of difference shown by the testing but would certainly allow the temporary usage to be fulfilled without imposing the cost of additional maintenance.

4.6 Retardation Evaluation

One of the research goals was to assess the retardation effect of the Al 2024-T351 material under a change in load history due to crack tip plasticity. This effect is of particular interest at the transition point when the loading is switched from Spectrum A to Spectrum B. A fatigue curve based on the absence of retardation was created for comparison to the actual A+B Combination data. This fatigue curve is based on the assumption that, if there is no retardation effect, then the shape of the fatigue curve after the transition point would follow the shape of the Spectrum B Baseline fatigue curve. This was achieved by normalizing the crack growth curve of Spectrum B of the surface crack at each transition point for Combinations A,B and C and comparing that curve to the crack growth curve from measured data for each combination.

This was obtained by using the process outlined in Figure 61 with the A+B Combination 3 as an example. This process involves selecting the data coordinates (EFH, surface crack size) corresponding to the transition point and locating the same surface crack size on the Spectrum B fatigue curve data. Then the EFH for the transition point is subtracted from the EFH related to the surface crack length of the transition point. Then that delta EFH is subtracted from each Spectrum B curve data which shifts the curve to align with the transition point shown in Figure 61. Since the AFGROW crack growth model agreed with the Spectrum B data, the AFGROW curve was used since there were more data points allowing for better opportunity to select the same surface crack length.

This process was performed for all of the A+B Combinations along with the measured data as shown in Figure 62. Since the area of concern is just after the transition, the A+B Transition Point Detail is shown in Figure 63 for the area just after the transition point, to roughly 75,000 EFH. By examination of the slopes of the fatigue curves for the actual data and the Normalized Baseline B curves, it can be seen that there is significant reduction in slope of the actual data as compared with Normalized Spectrum B curve, which assumes there is no retardation. This change in slope of the fatigue growth curves became more pronounced as the bore crack length grew for each combination switch point.

This follows from the Crack Tip Plasticity Theory which predicted that the plastic zone would increase as the stress intensity, K, increased which is a function of crack growth length.

Table 10 Spectrum Combination Data

Test Combination	Spectrum Detail				Experiment Description	Process
	Maximum Stress (psi)	Minimum Stress (psi)	# of Endpoints per block	# of Equivalent Flight Hours per block		
Baseline A	27,898	-1.682	14,737	240	Represents Aggressive Flight Loading Spectrum	Test using spectrum A to full fracture
Baseline B	23,040	-1,807	4,373	1000	Represents Benign Flight Loading Spectrum	Test using spectrum B to full fracture
A + B Combo 1	27,898	-1.807	Combination of A & B	Combination of A & B	Models switching from aggressive Flight Loading to benign in the early stages of part life	Test using Spectrum A until bore crack reaches 0.20 in, then switch to spectrum B
A + B Combo 2	27,898	-1.807	Combination of A & B	Combination of A & B	Models switching from aggressive Flight Loading to benign in the mid life portion of part life	Test using Spectrum A until bore crack reaches .80*t, then switch to spectrum B
A + B Combo 3	27,898	-1.807	Combination of A & B	Combination of A & B	Models switching from aggressive Flight Loading to benign in the mature life portion of part life	Test using Spectrum A until bore crack reaches full thickness, then switch to spectrum B

Table 11 Test Matrix

Specimen ID	Specimen Type	Loading Type	Spectrum Combination	Fatigue Lab	Test Date	Stress (ksi)	Cycles to Ligament Failure	Flight Hours to Ligament Failure	Flight Hours to End of Inspection Interval
2024-1	ASTM E 647 M(T)	Constant Amplitude	NA	Hill AFB	17-May-13	11.85	66244	NA	NA
2024-2	ASTM E 647 M(T)	Constant Amplitude	NA	Hill AFB	20-May-13	11.85	34244	NA	NA
GT270KB003-11-4	M(T) Specimen	Variable Amplitude	Spectrum A Baseline	Hill AFB	1-Aug-13	27.9	NA	23136	NA
GT270KB003-11-11	M(T) Specimen	Variable Amplitude	Spectrum A + B Combination 2	Hill AFB	21-Aug-13	27.9	NA	572410	NA
GT270KB003-11-6	M(T) Specimen	Variable Amplitude	Spectrum A + B Combination 1	Hill AFB	3-Sep-13	27.9	NA	NA	104455
GT270KB003-11-13	M(T) Specimen	Variable Amplitude	Spectrum A + B Combination 3	Hill AFB	4-Sep-13	27.9	NA	NA	126350
GT270KB003-11-29	M(T) Specimen	Variable Amplitude	Spectrum B Baseline	Hill AFB	11-Sep-13	23.04	NA	543632	NA
GT270KB003-11-12	M(T) Specimen	Variable Amplitude	Spectrum A + B Combination 3	Hill AFB	17-Sep-13	27.9	NA	NA	130629
GT270KB003-11-7	M(T) Specimen	Variable Amplitude	Spectrum A + B Combination 1	SWRI	6-Feb-14	27.9	NA	NA	192088
GT270KB003-11-10	M(T) Specimen	Variable Amplitude	Spectrum A + B Combination 2	SWRI	14-Feb-14	27.9	NA	NA	210382
GT270KB003-11-1	M(T) Specimen	Variable Amplitude	Spectrum A Baseline	SWRI	3-Mar-14	27.9	NA	30552	NA
GT270KB003-11-9	M(T) Specimen	Variable Amplitude	Spectrum A + B Combination 3	SWRI	20-Mar-14	27.9	NA	NA	270039
GT270KB003-11-27	M(T) Specimen	Variable Amplitude	Spectrum B Baseline	SWRI	27-Mar-14	23.04	NA	534973	NA
GT270KB003-11-5	M(T) Specimen	Variable Amplitude	Spectrum A Baseline	Hill AFB	14-Feb-14	27.9	NA	30519	NA
GT270KB003-11-8	M(T) Specimen	Variable Amplitude	Spectrum A + B Combination 2	Hill AFB	21-Feb-14	27.9	NA	NA	211164
GT270KB003-11-3	M(T) Specimen	Variable Amplitude	Spectrum A + B Combination 1	Hill AFB	24-Feb-14	27.9	NA	NA	161544
GT270KB003-11-28	M(T) Specimen	Variable Amplitude	Spectrum B Baseline	Hill AFB	2-Mar-14	27.9	NA	519100	519100
GT270KB003-11-30	M(T) Specimen	Variable Amplitude	Spectrum A Baseline	Hill AFB	14-Mar-14	27.9	NA	32738	NA
GT270KB003-11-31	M(T) Specimen	Variable Amplitude	Spectrum A + B Combination 2	Hill AFB	17-Mar-14	27.9	NA	NA	191861

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-27
Width: ___4.00 in_______ Thick:__.410 in_________ Area: 1.64 in^2

Precrack Information

Precrack Date: July 15, 2013____ Loading Condition: Constant Amplitude R=.05_____
Frequency:_5 hz___________ Hole Diameter:0.156 in_ Peak Stress:_19.5 ksi____
Surface EDM Length: 0.0303 in_____________

Testing Information

Test Date: March 27, 2014 Loading Condition:_Variable Amplitude_
Constant Load Rate:100 kip/sec Spectrum:__Baseline Spectrum B
____
Surface EDM Length:_.042 in Hole Diameter:_.250 in
Peak Stress:__27.9 ksi___________

EFH	Crack Length (inches)			
	EDM Side		Opposite Side	
	Front	Back	Front	Back
0	0.042			
91470.39	0.085			
137205.6	0.117			
182940.8	0.1505			
228676	0.1975			
274411.2	0.2555			
304139	0.298	0.004		
324719.9	0.327	0.182		
333866.9	0.3425	0.218		
365881.5	0.403	0.32		
402469.7	0.481	0.4255		
425337.3	0.551	0.499		
443631.4	0.603	0.557		
461925.5	0.6625	0.626		
480219.5	0.7365	0.7075		
498513.6	0.83	0.814	0.124	0.153
508118	0.8905	0.8705	0.18	0.2105
516807.7	0.9745	0.9495	0.2415	0.2775
521381.2	1.014	1.004	0.282	0.321
530528.2	1.158	1.148	0.414	0.441
534973.7	Final Specimen Fracture			

Figure 41 Specimen Data Sheet

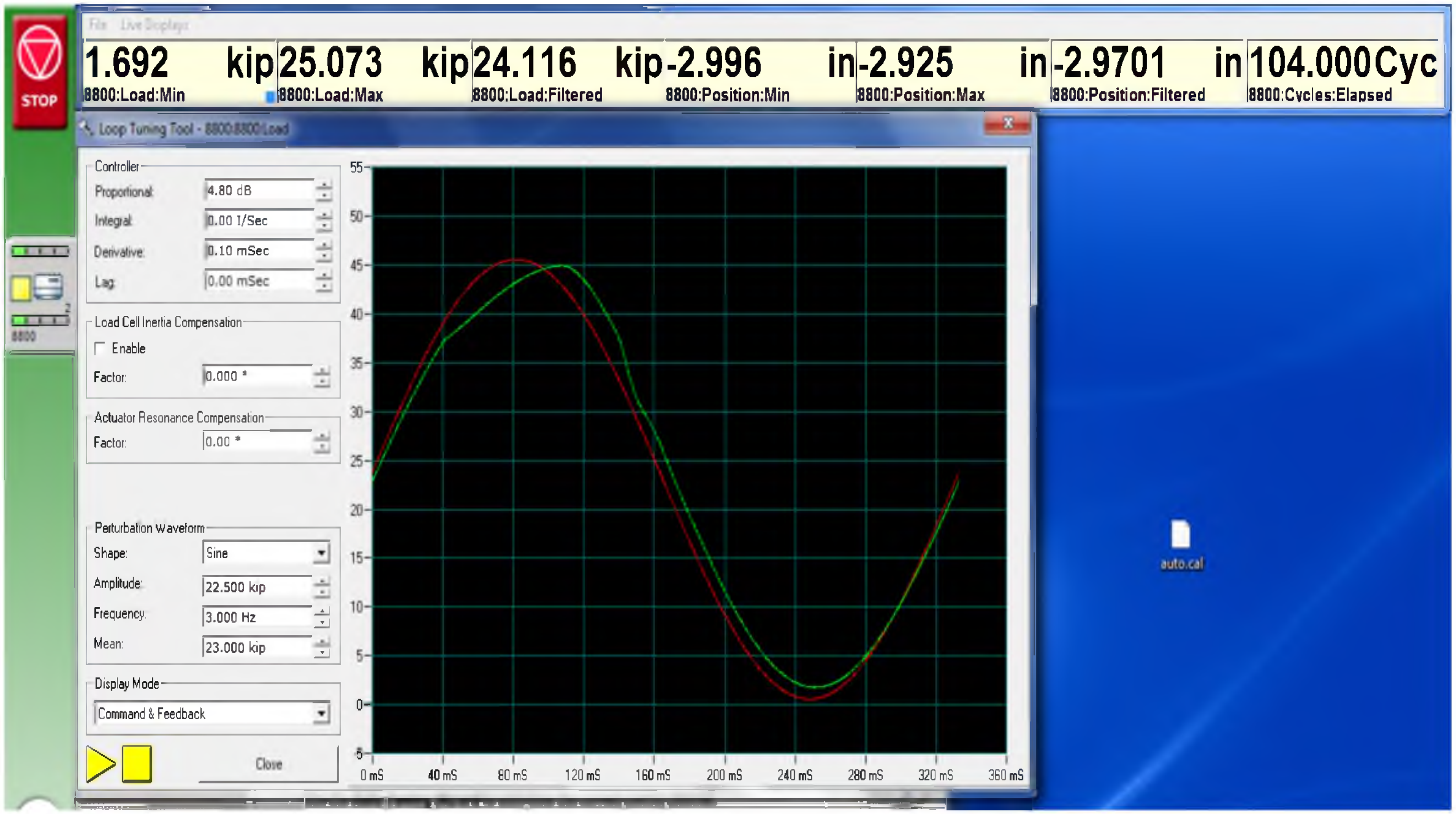


Figure 42 Instron Tuning Tool Screenshot - Command load in red and feedback load in green

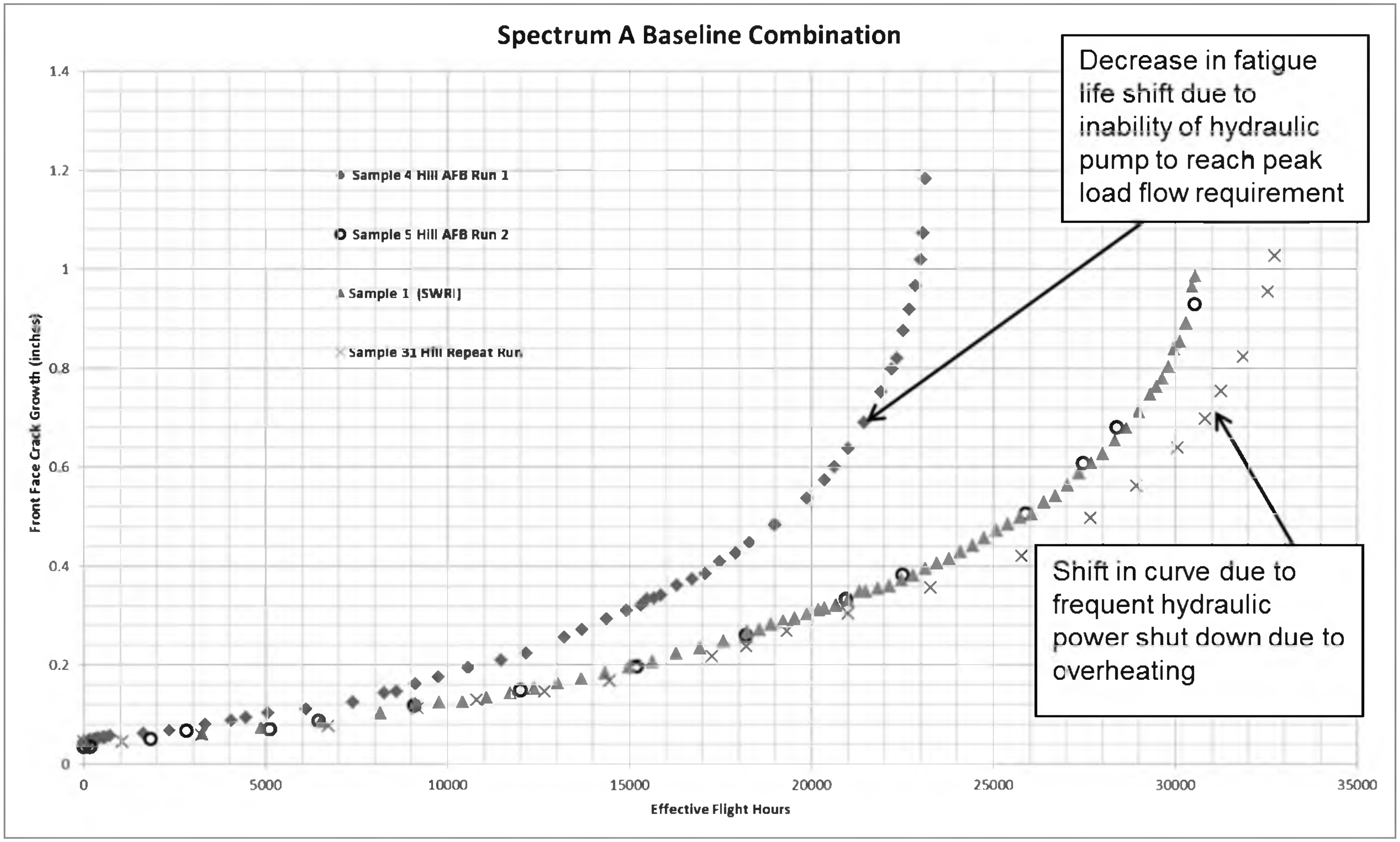


Figure 43 Spectrum A Baseline Crack Growth

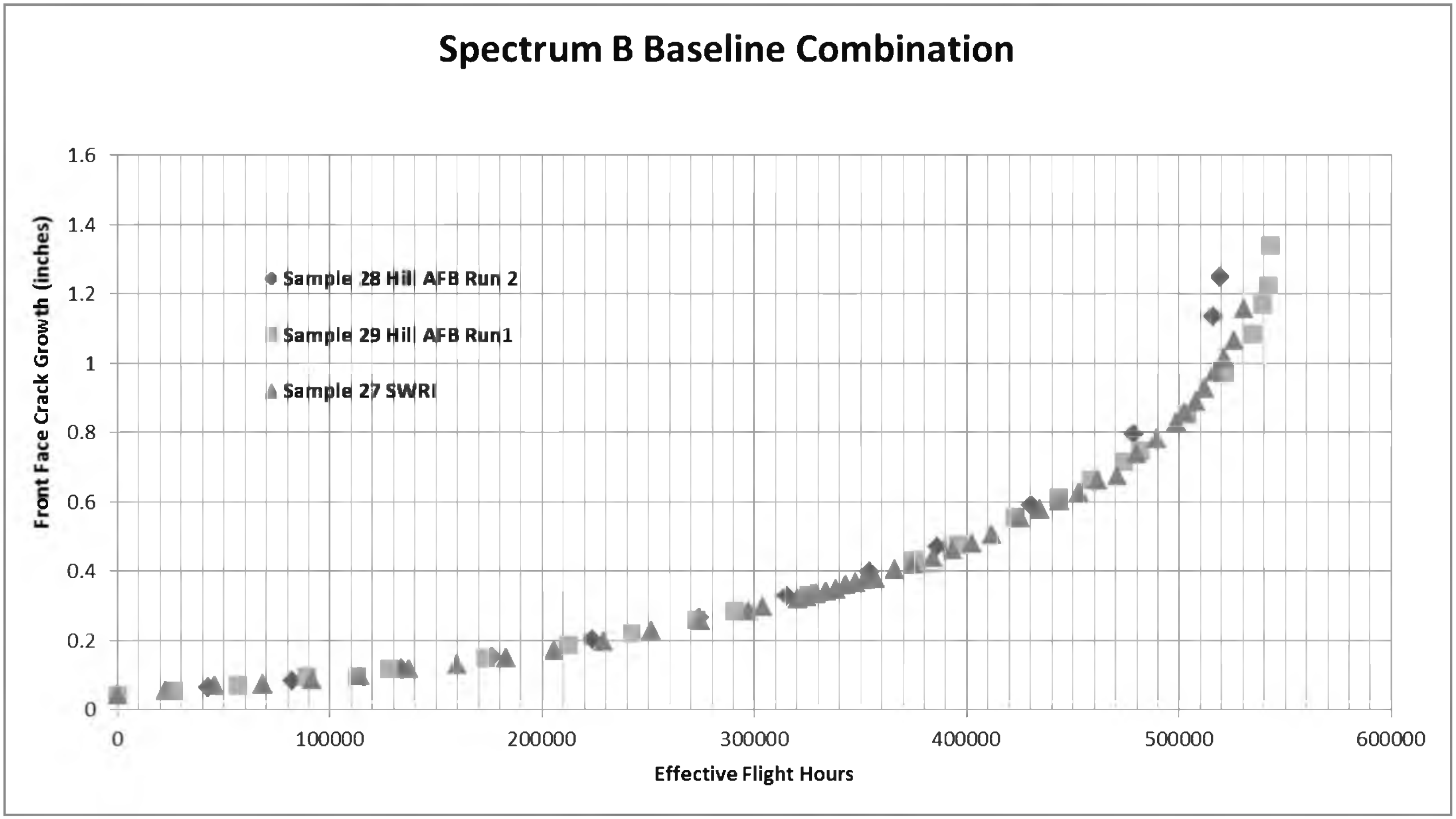


Figure 44 Spectrum B Baseline Crack Growth Curve

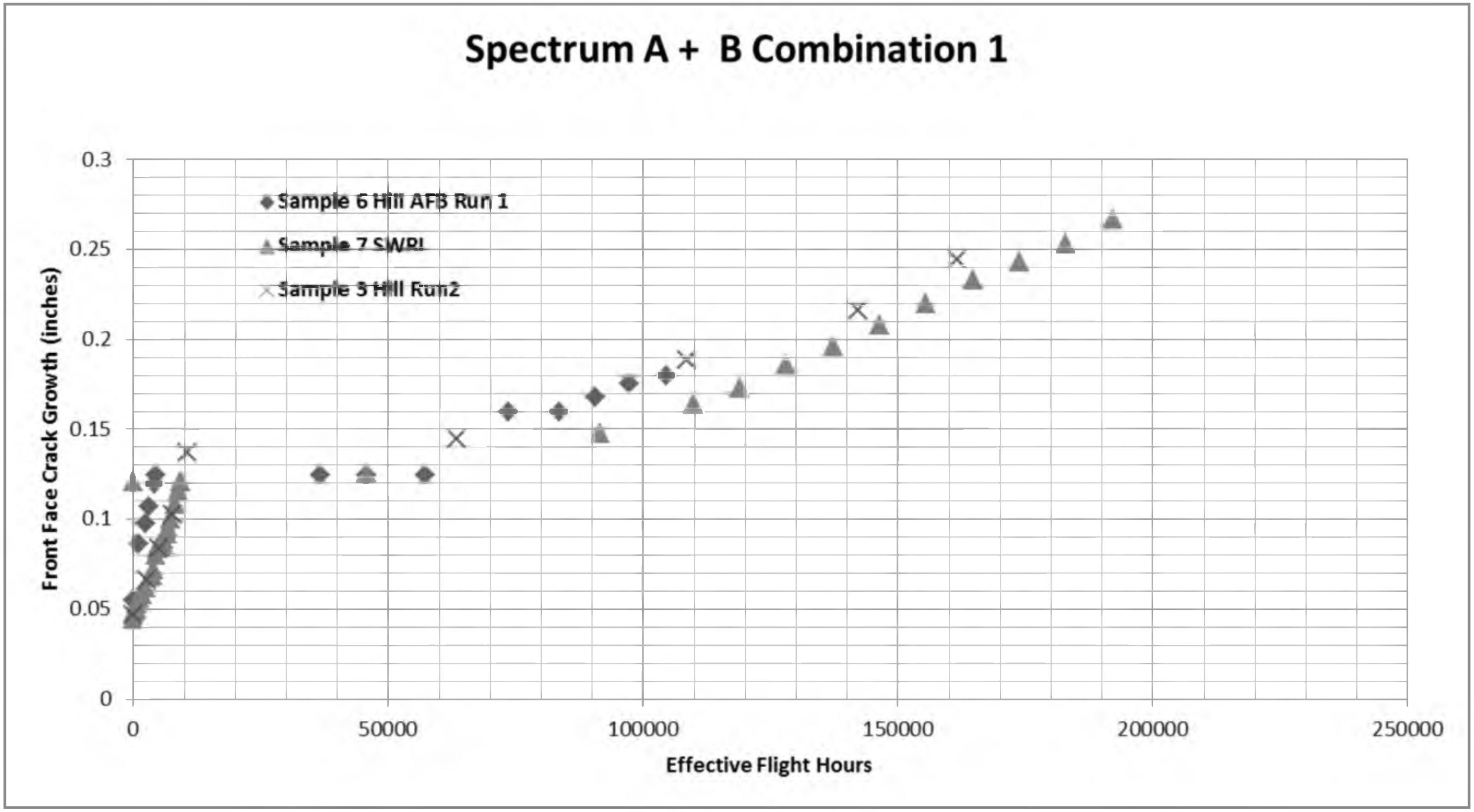


Figure 45 Spectrum A + B Combination 1 Crack Growth Curve

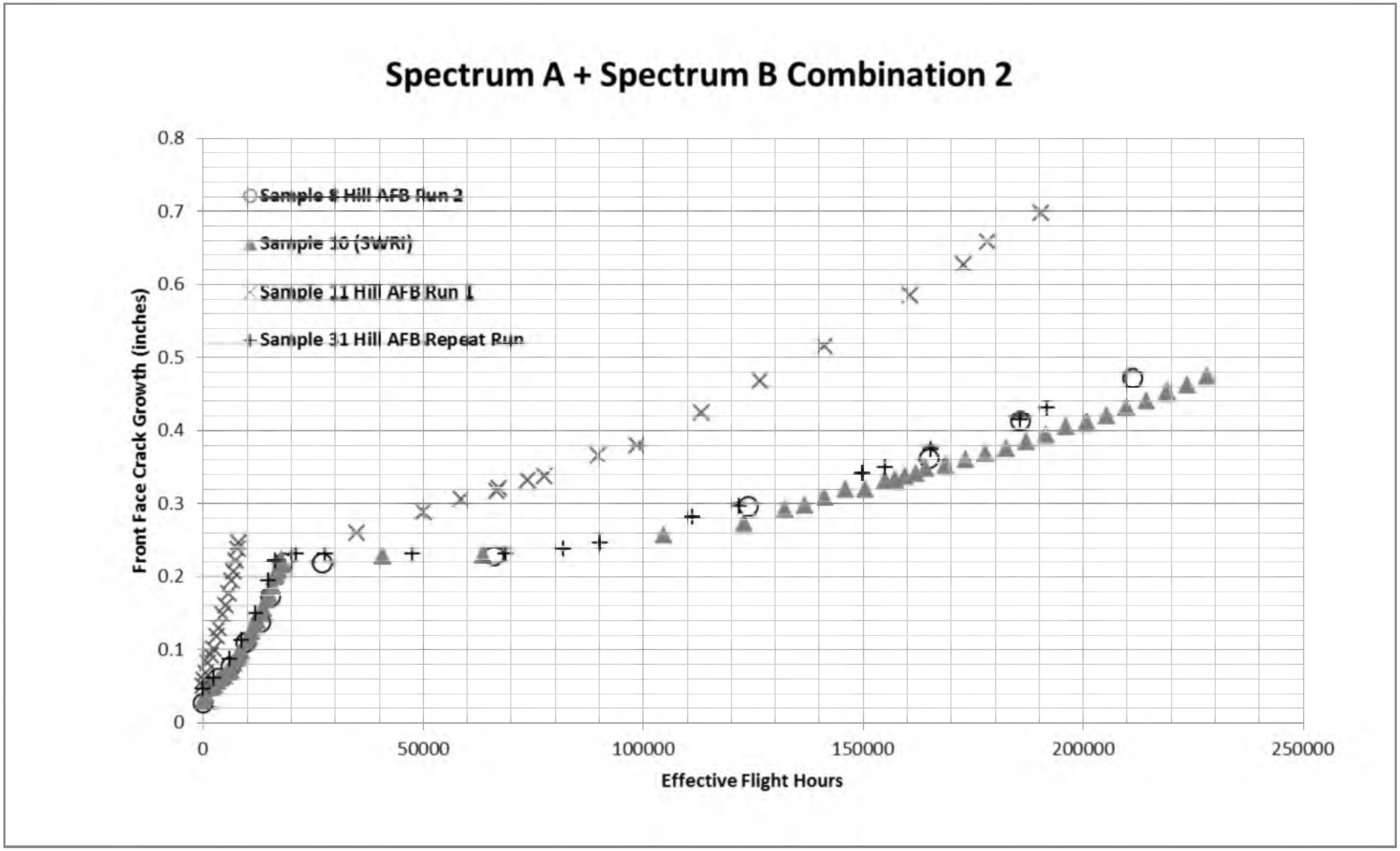


Figure 46 Spectrum A + B Combination 2 Crack Growth Curve

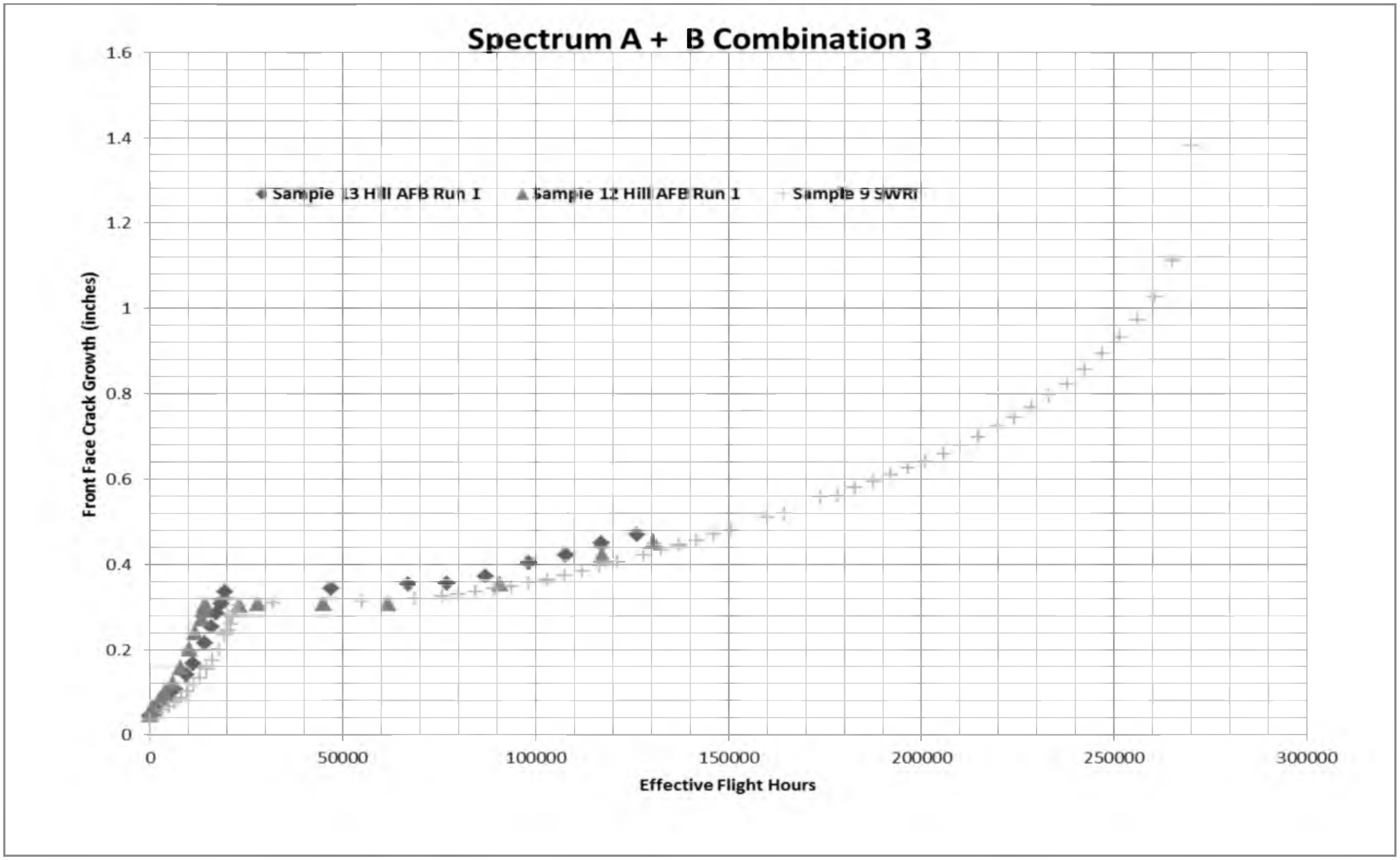


Figure 47 Spectrum A + B Combination 3 Crack Growth Curve

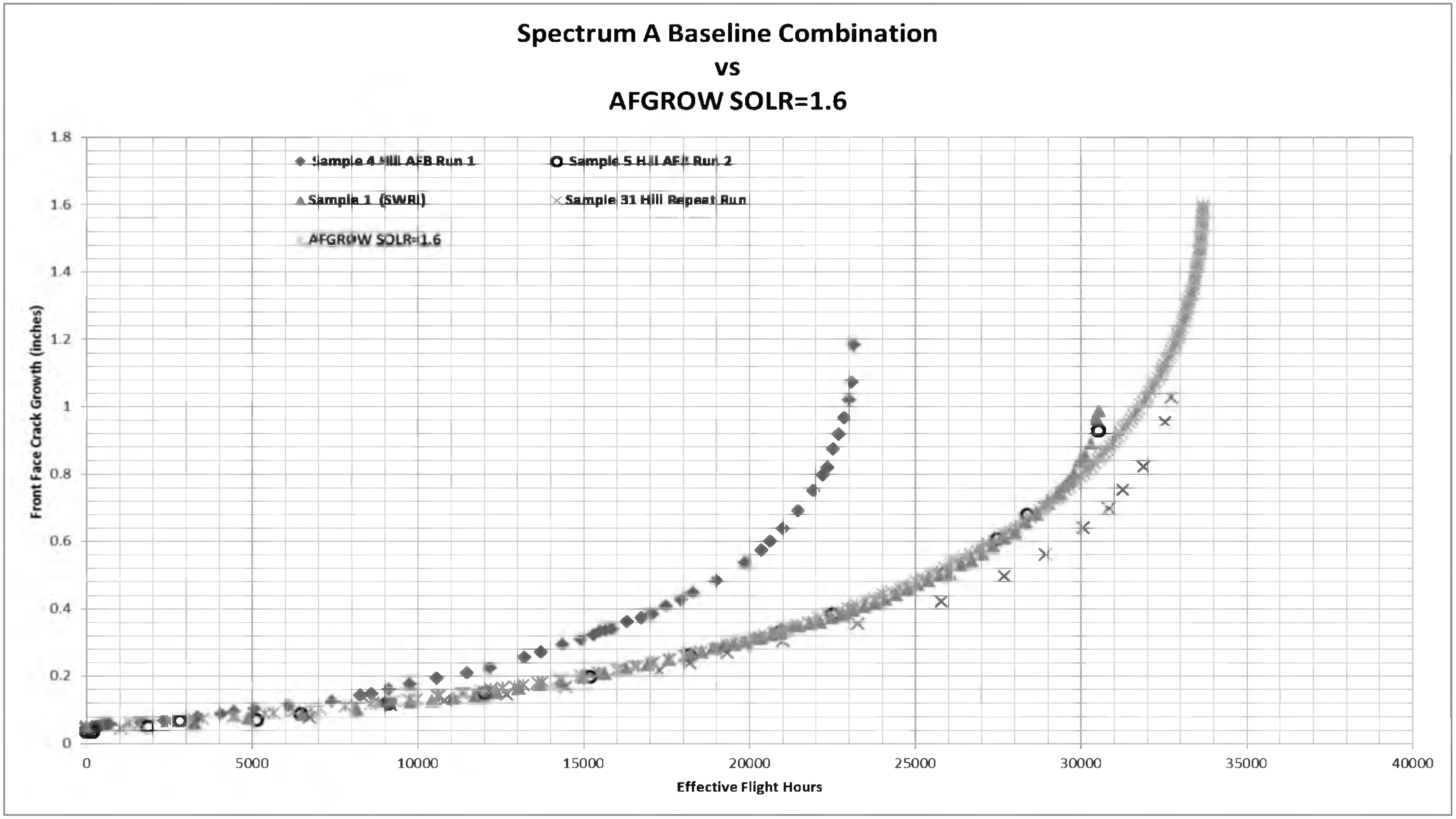


Figure 48 Baseline Spectrum A Specimen AFGROW SOLR Plots

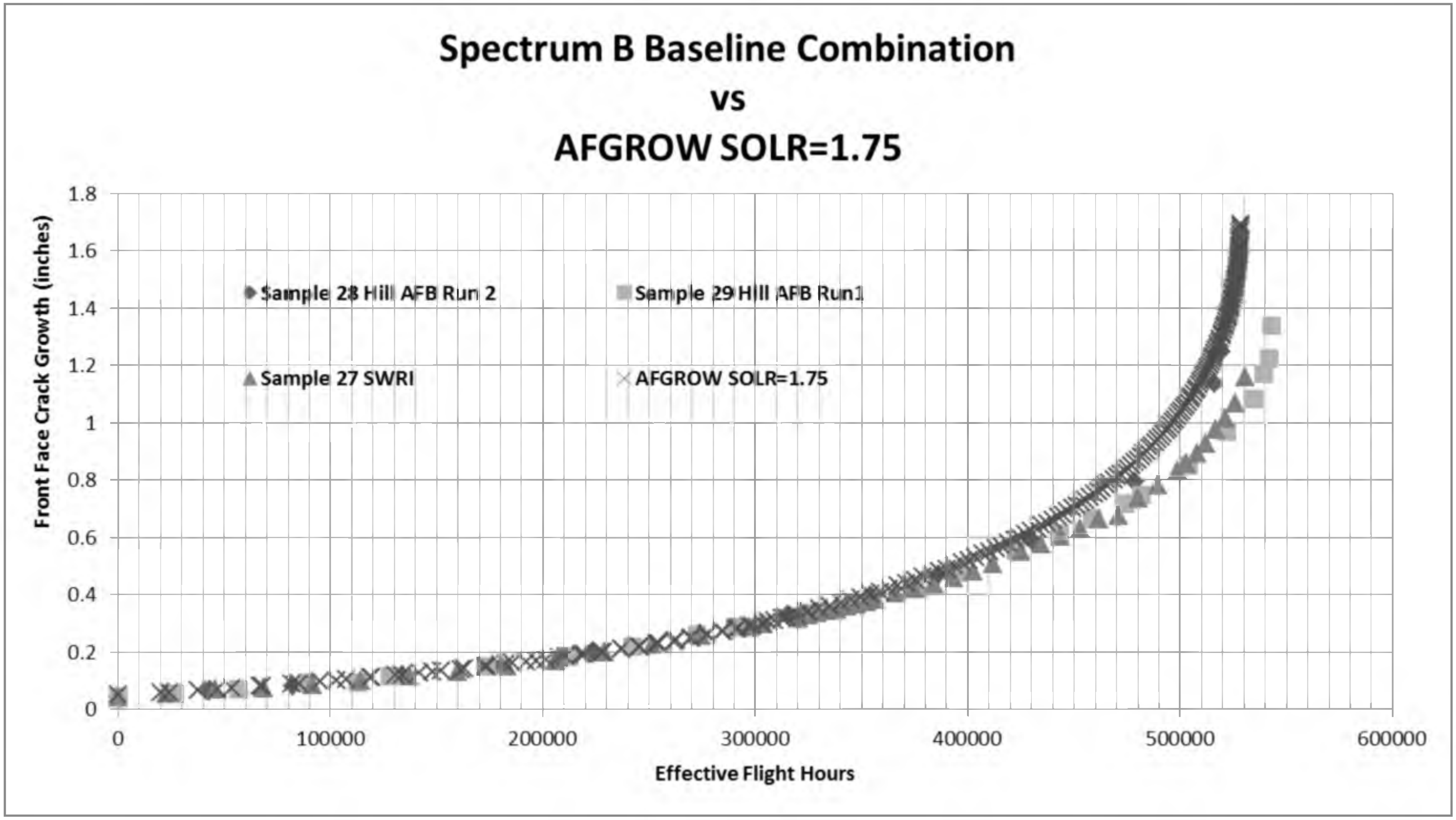


Figure 49 Baseline Spectrum B Specimen AFGROW SOLR Plots

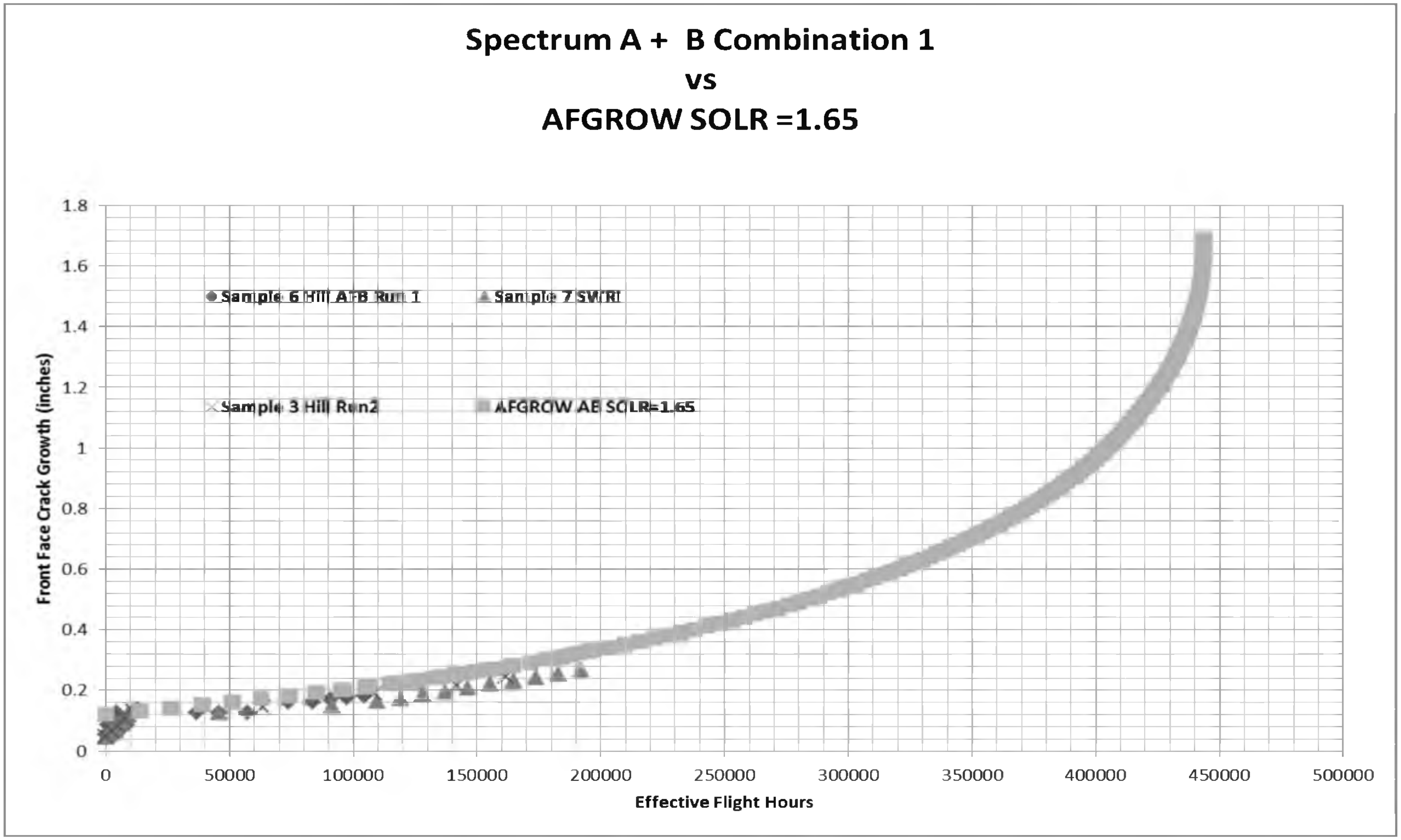


Figure 50 Spectrum A + B Combination 1 Specimens AFGROW SOLR Plots

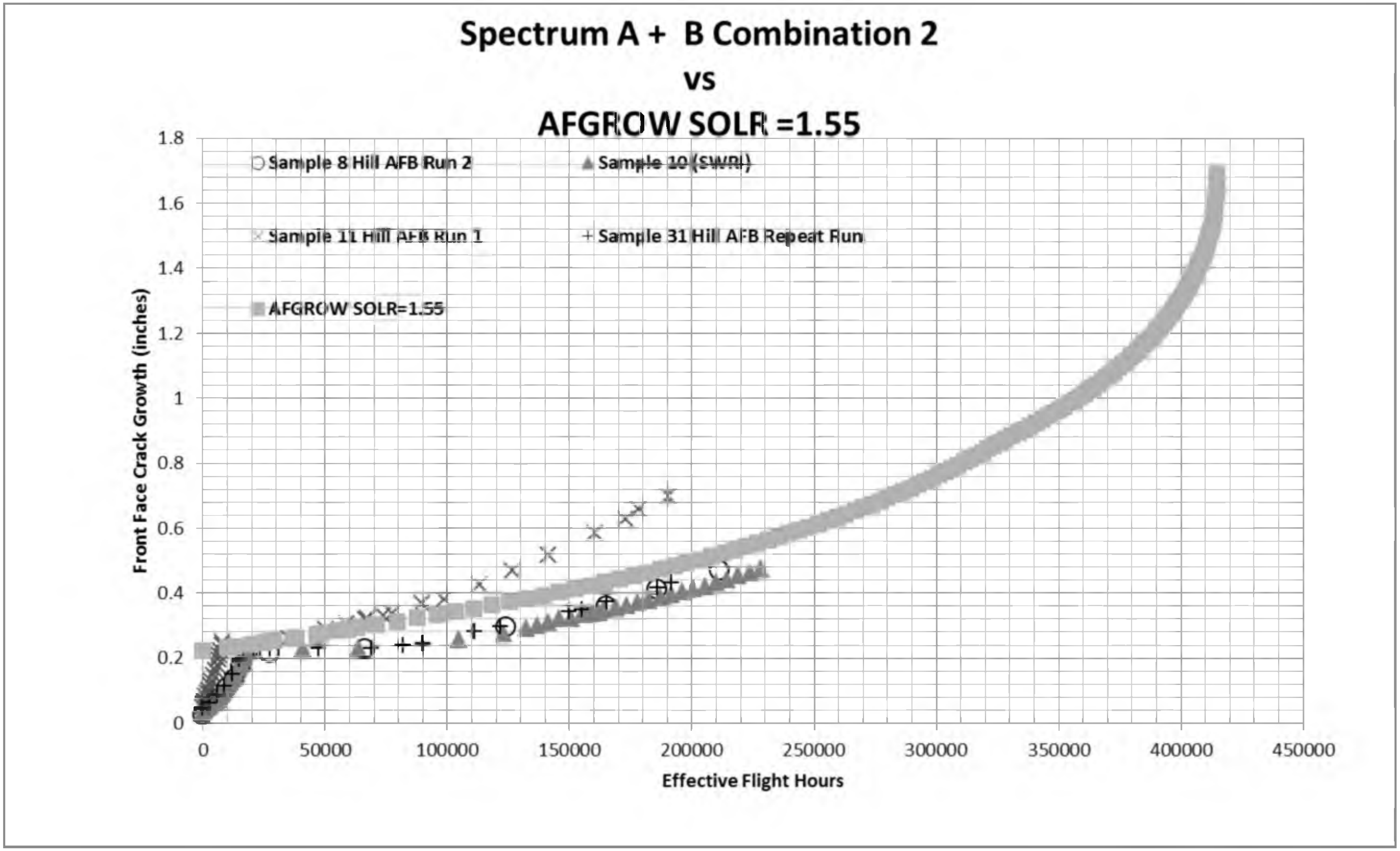


Figure 51 Spectrum A + B Combination 2 Specimens AFGROW SOLR Plots

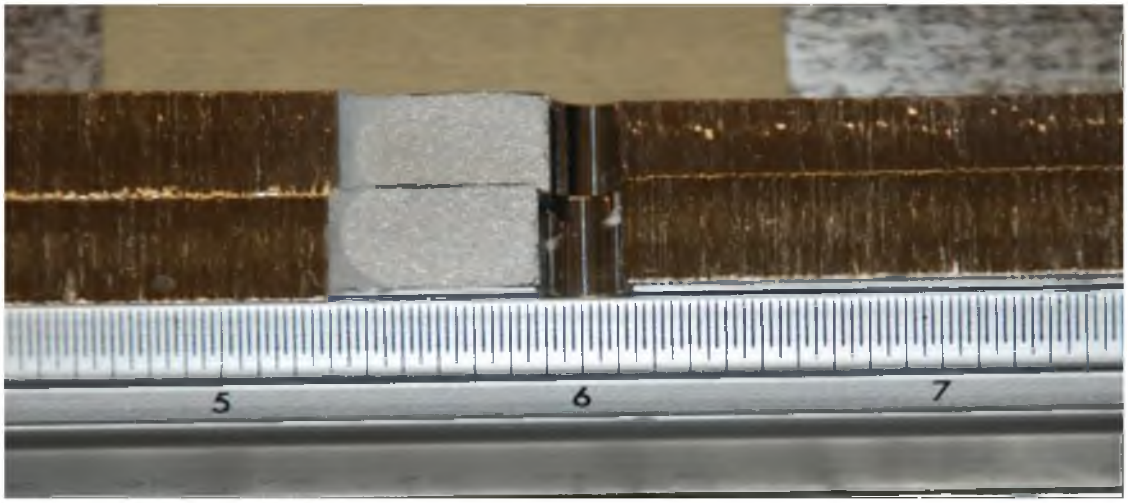


Figure 52 Sample 13

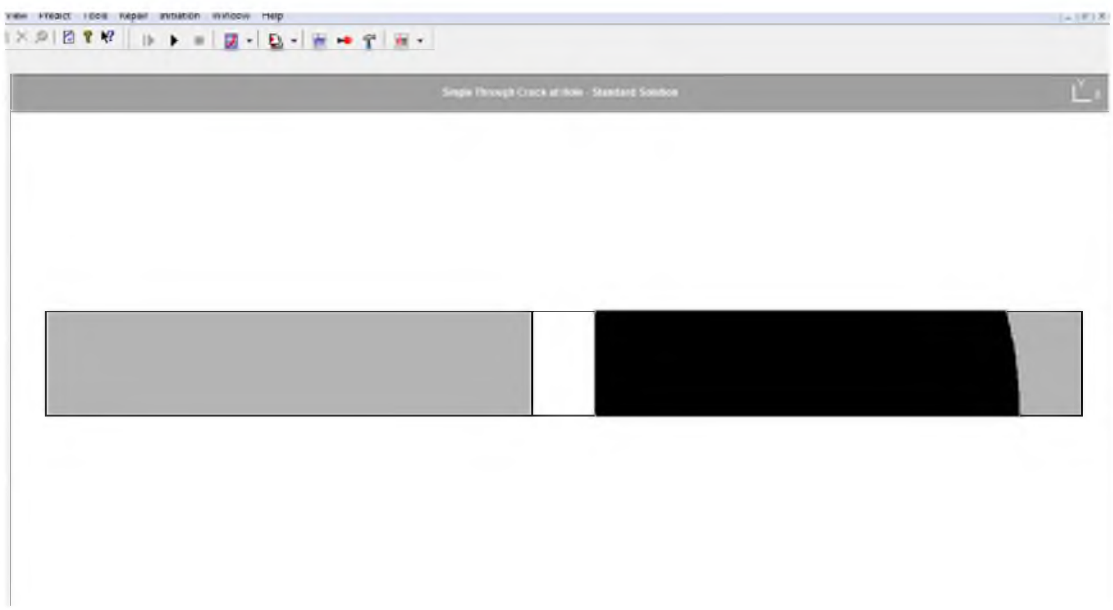


Figure 53 Spectrum A + B Combination 3 Specimens AFGROW Final Crack Growth Profile

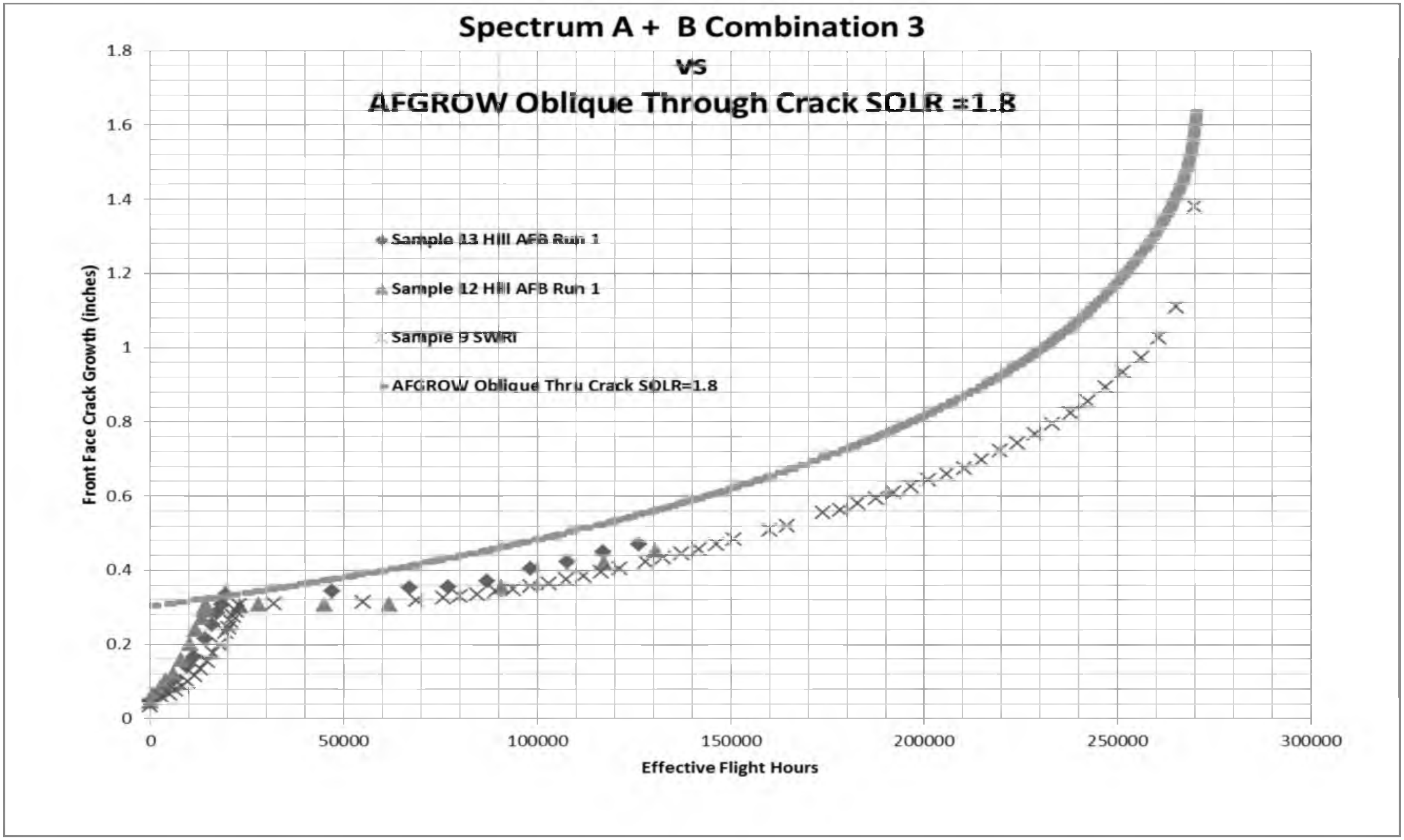


Figure 54 Spectrum A + B Combination 3 Specimens AFGROW SOLR Plot – Oblique Through Crack

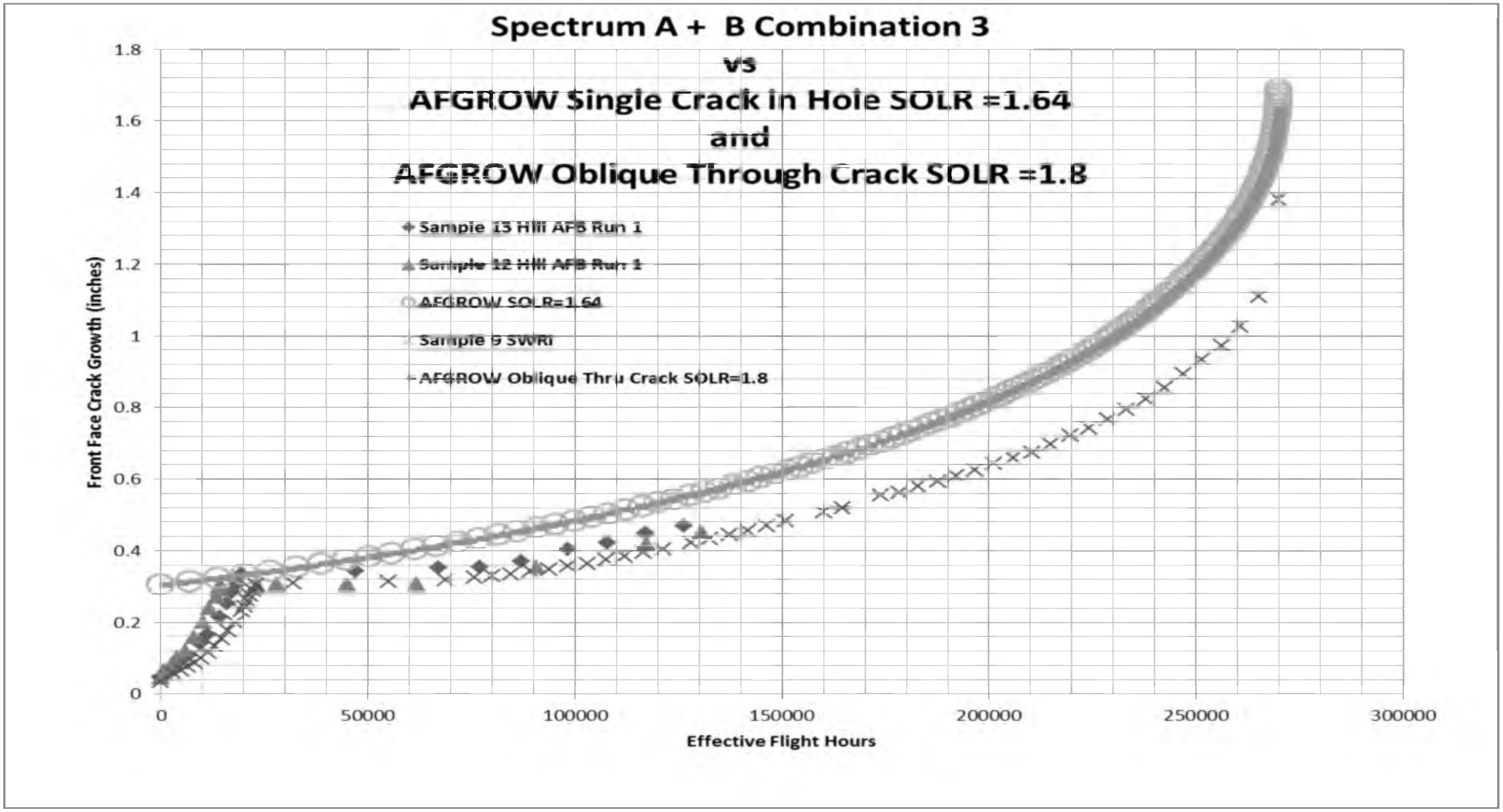


Figure 55 Spectrum A + B Combination 3 Specimens AFGROW Combined

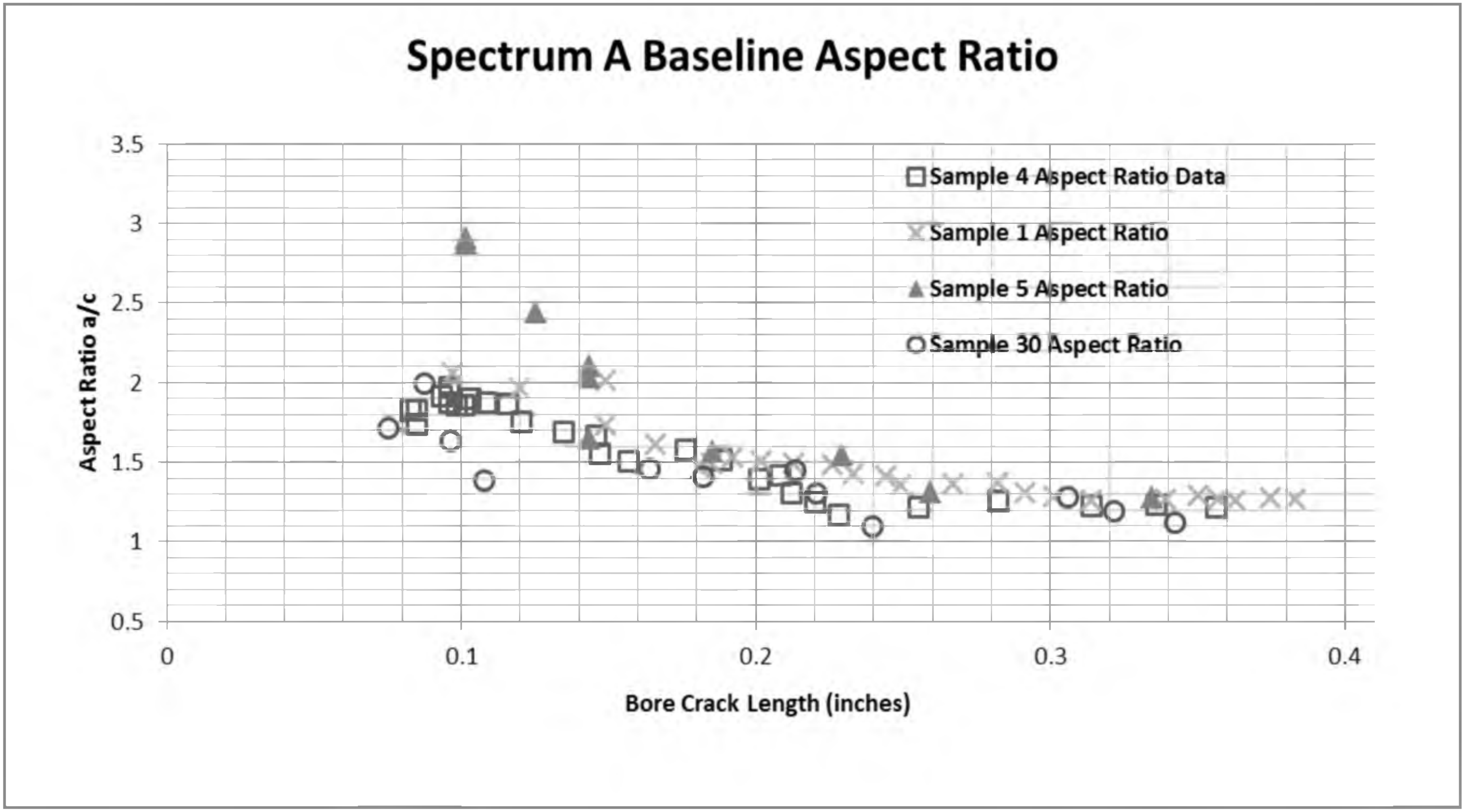


Figure 56 Spectrum A Baseline Aspect Ratios

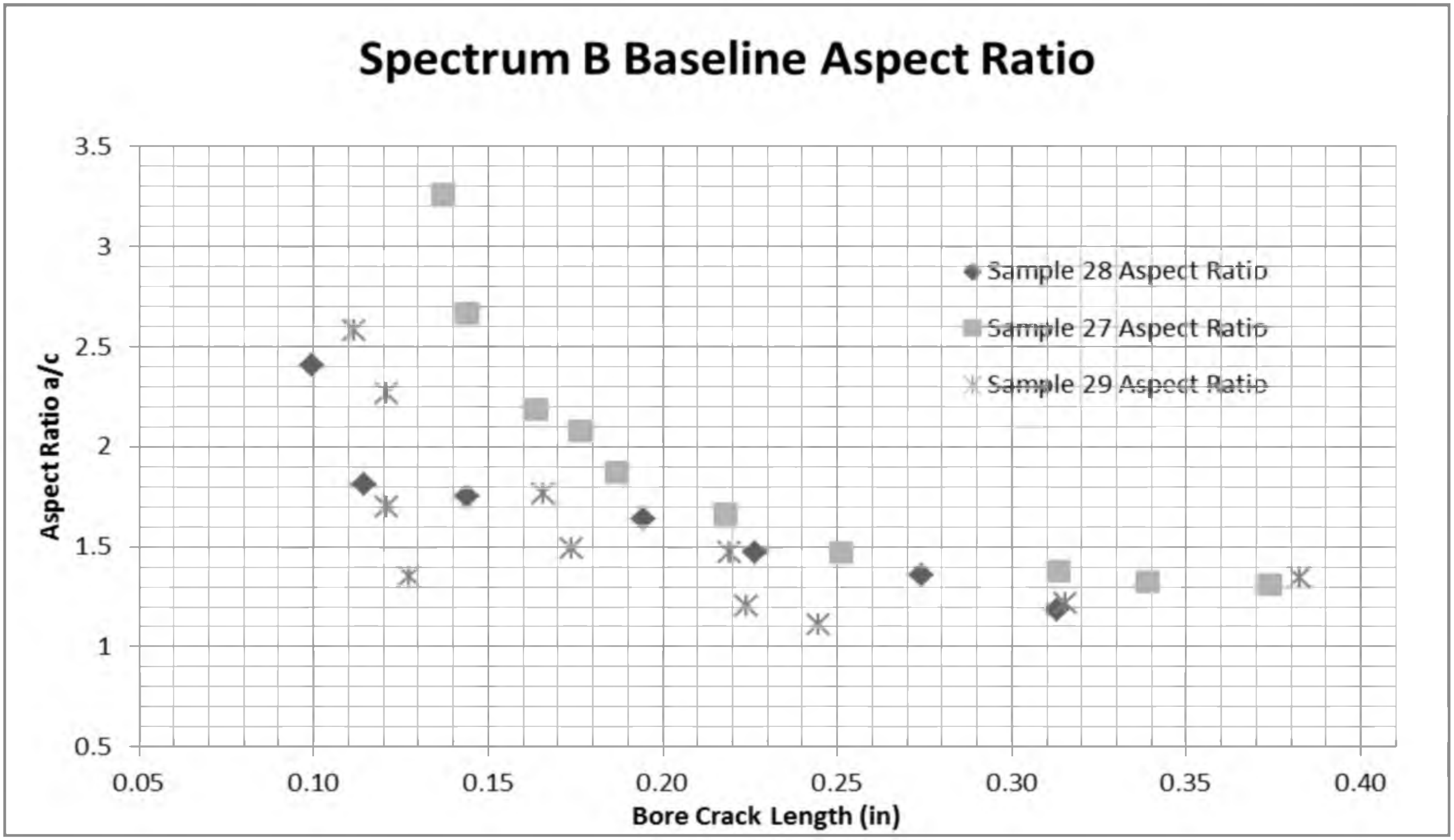


Figure 57 Spectrum B Baseline Aspect Ratio

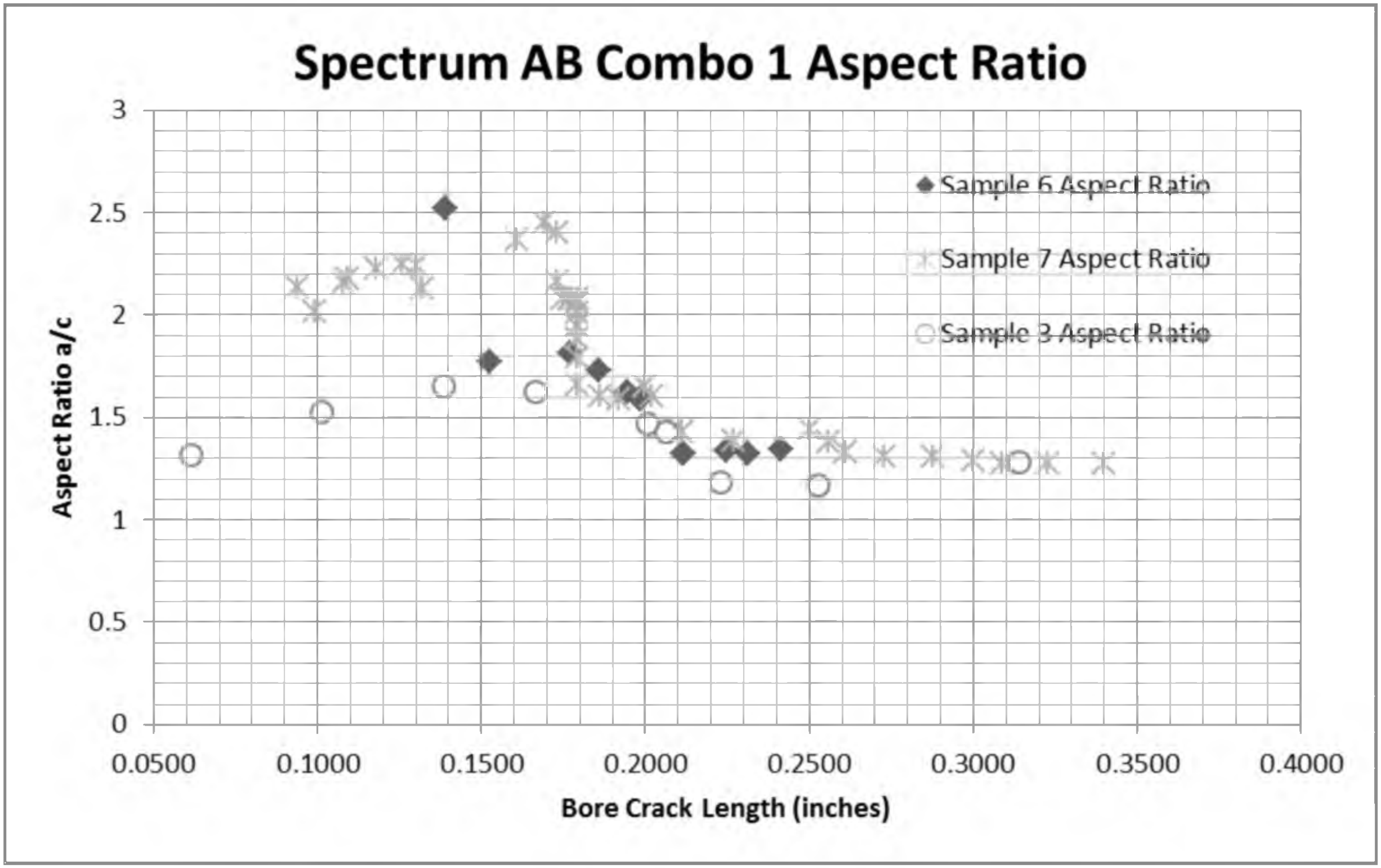


Figure 58 Spectrum A+B Combination 1 Aspect Ratio

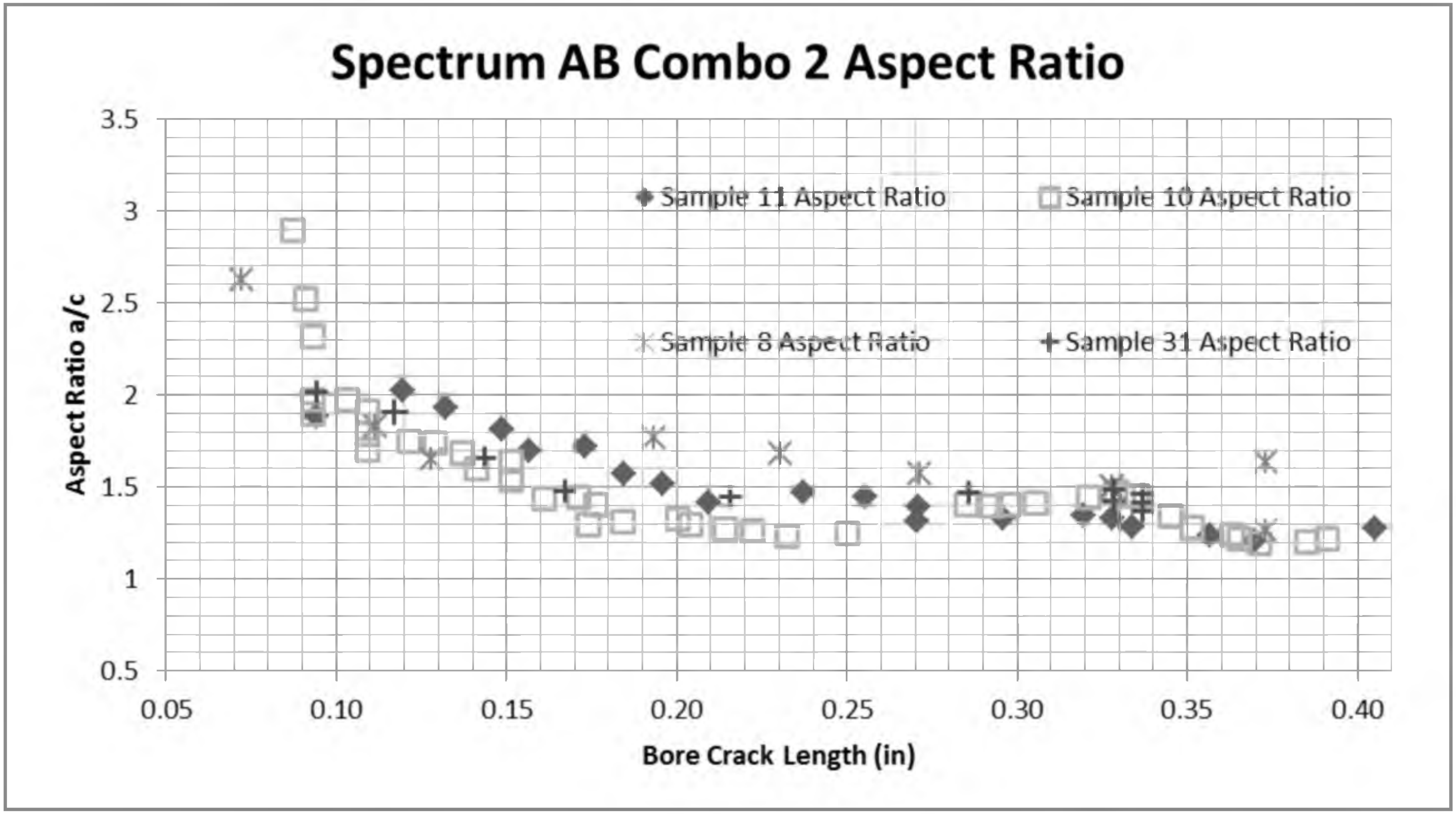


Figure 59 Spectrum A+B Combination 2 Aspect Ratio

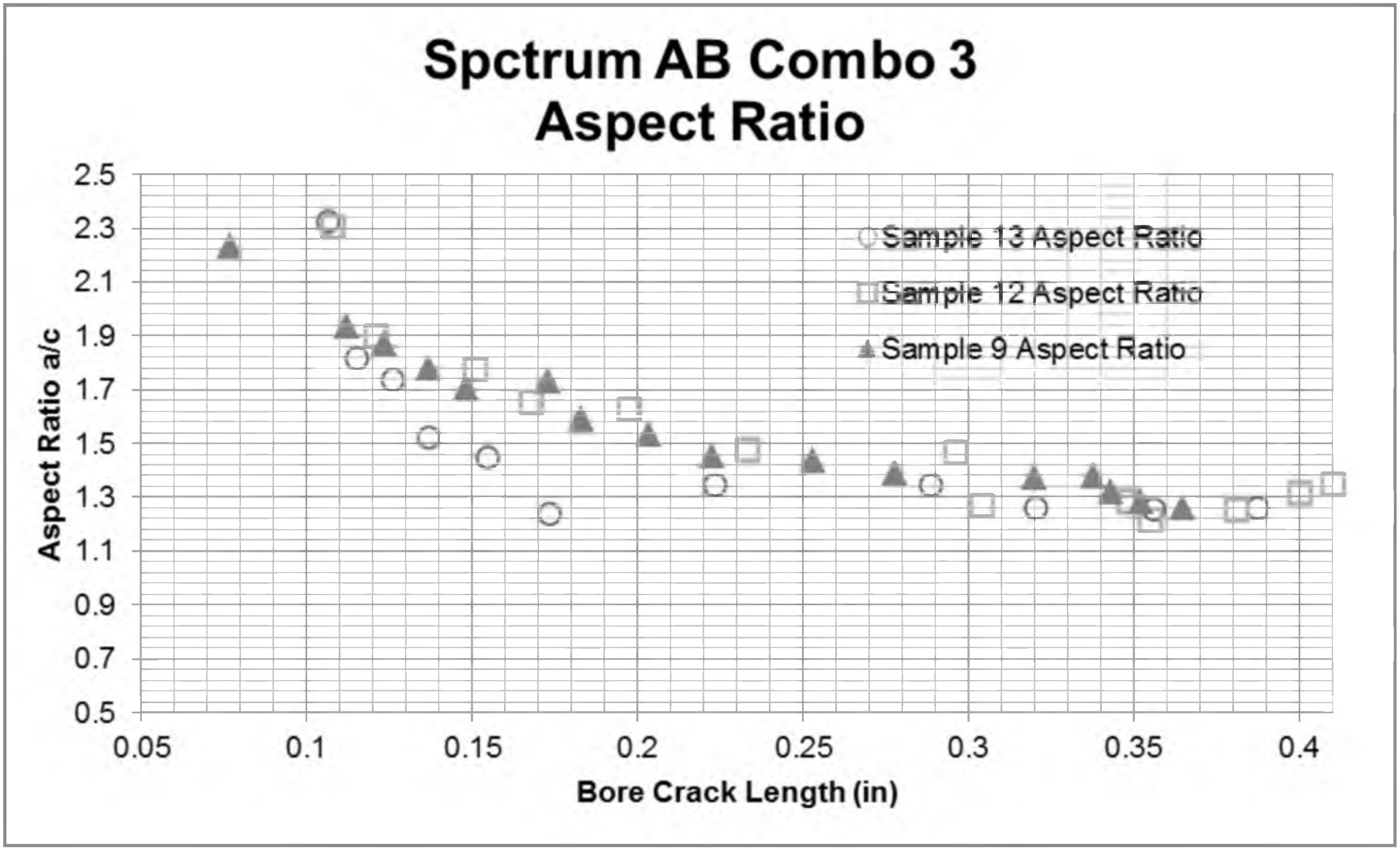


Figure 60 Spectrum A+B Combination 3 Aspect Ratio

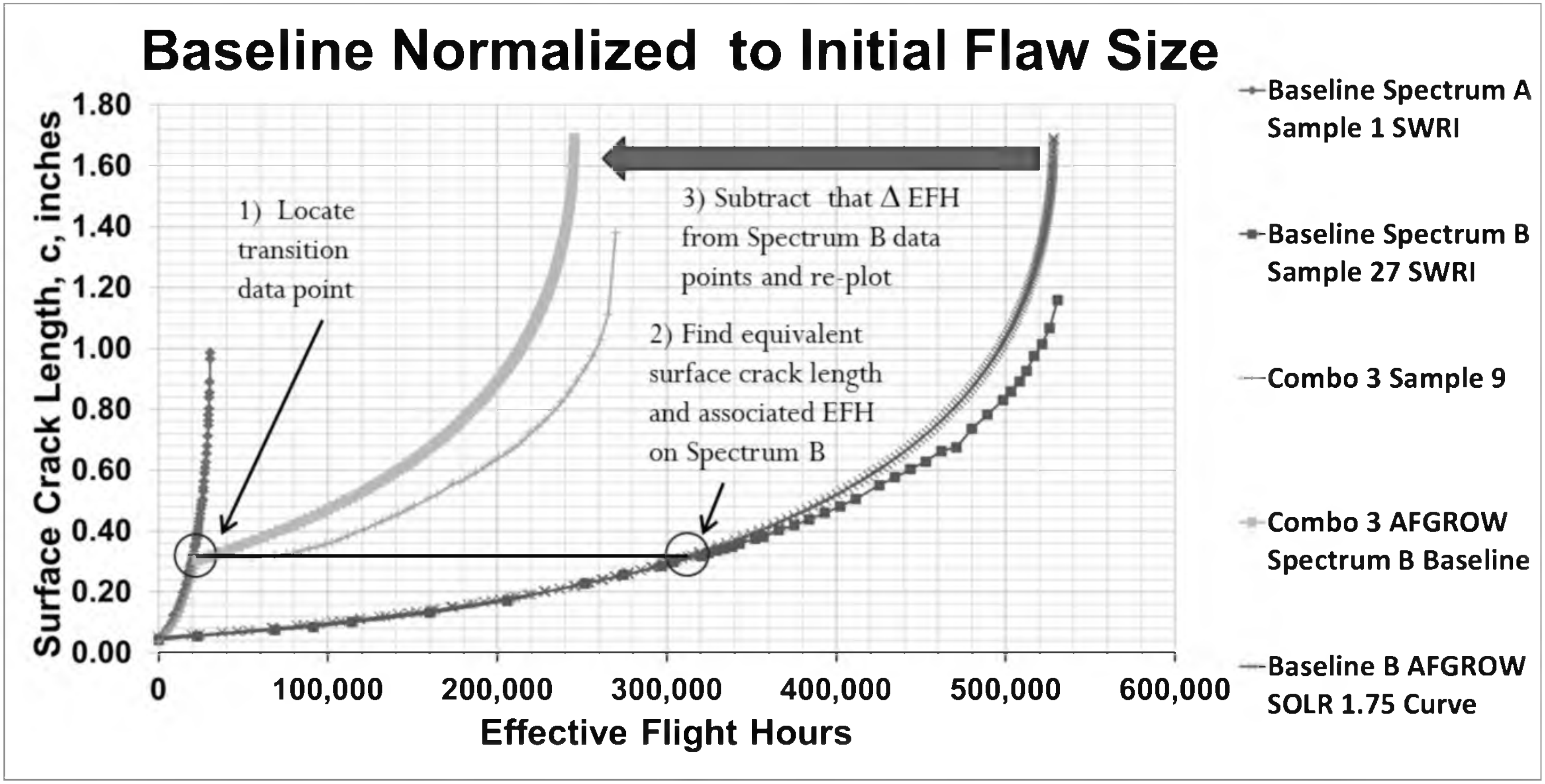


Figure 61 Spectrum B Normalized to Initial Flaw Size - A+B Combination 3 as example

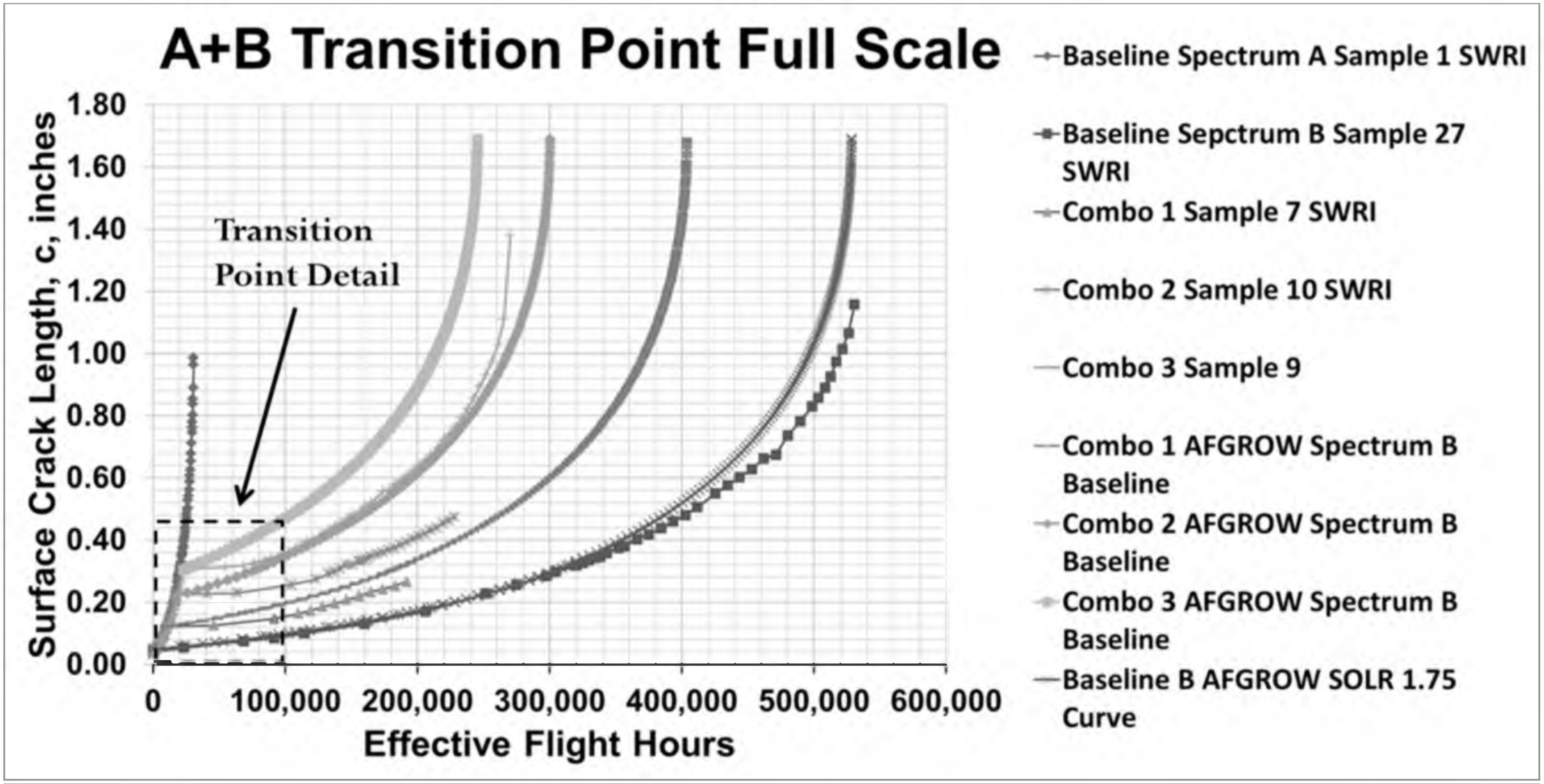


Figure 62 Normalized Fatigue Curves for all A+B Combinations

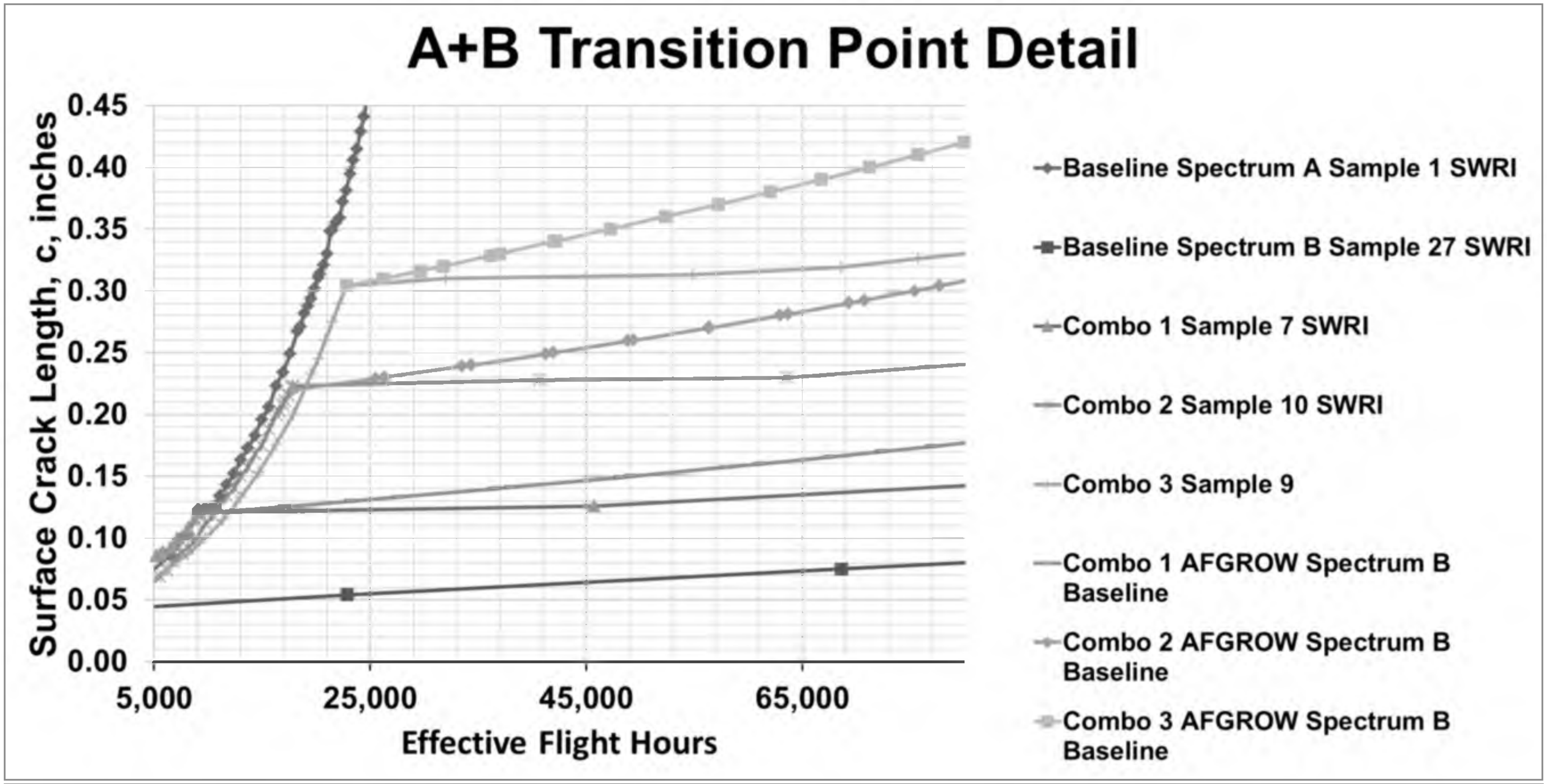


Figure 63 Retardation Zone at AB Combination Transition Point

CHAPTER 5

FRACTOGRAPHY

The purpose of this fractographic examination is to verify the transition areas from precracking zone to Spectrum A and from Spectrum A to Spectrum B, to compare and contrast the crack surfaces for each loading area. Since the material used for this experiment, Aluminum 2024-T351, is expected to be sensitive to the overload conditions, the crack surfaces were examined for indications of overloading and retardation. The macro surface work was accomplished at the Hill AFB Bldg 100 laboratory using Serial # 63803 Nikon D40X camera. The micro surface photographs were obtained from the Hitachi S-2600N SEM at the University of Utah.

Previous research on fractographic examination of Al 2024-T351 and other aluminum alloys was consulted for this experiment. The work of Wanhill related to fractographic examination of aluminum alloys under constant amplitude loading was useful for comparing surfaces of constant amplitude loading, which pertains to the precracking zone for this experiment, and the surfaces under variable amplitude loading.[42] Previous work by Bogdanowicz and others in 2009 indicated a surface detail confirming the effect of overloads and subsequent retardation as follows:

> Applying a single overload in base cycles resulted in either a sudden crack growth rate jump or its rapid drop by one order of magnitude. Load interaction lead to a delayed retardation of crack growth and then to its gradual increase in the phase corresponding to the application of successive 100 base cycles.[43]

From the literature research, fractographs of 2024 and 7075 aluminum alloy material under constant and variable amplitude loading was useful for providing features or patterns to look for in this experiment. The striation pattern shown in the SEM photograph in Figure 64 of an aluminum alloy sheet fracture surface was observed in the SEM work from this experiment. [44] The fracture surface photograph from the study by Bogdanowicz shown in Figure 65 compares the fatigue crack growth front from a variable amplitude loading area to that of a constant amplitude loading area.[45] In the work of Stephens and others, the overload extension pattern and the subsequent retardation region on the surface of the 2024-T3 aluminum material were identified and are shown in Figure 66. This pattern is identifiable in several of the SEM fractographs taken from this experiment. The article by Bogdanowicz also noted the change in direction related to inclusions in the material. This was detected in the fractographs from this work and is identified in the photographs in this chapter.

This section is organized by the five types of loading combinations: Baseline A Spectrum Loading, Baseline B Spectrum Loading, and the three combinations A+B 1, 2 and 3. Each section has a macro image, taken with Serial # 63803 Nikon D40X camera from the Hill AFB lab, of the fracture specimens for reference followed by a micro image taken from the SEM lab at the University of Utah. These images start at the EDM notch location of the bore and follow the semielliptical crack front down the bore towards the back surface. The photographs capture the crack surface details related to each stage of the loading history from precracking to the spectrum loading portion and identify specific areas of interest.

5.1 Baseline Spectrum A

The macro fracture face profile for specimen G270KB003-11-4 which was under the Spectrum A , variable amplitude loading, until full fatigue fracture is shown in Figure 67. Note that there was secondary cracking on the non-EDM side with multiple bore crack nucleation sites. This is of importance when comparing the AFGROW crack growth analysis which only accounts for cracking on the EDM side of the bore and predicts a longer fatigue life under this loading. Note the characteristic shear lips shown on the right side of Figure 67.

The SEM image in Figure 68 shows the location of the EDM notch side and the direction of crack growth for specimen G270KB003-11-4. The precracking zone for this specimen is shown in Figure 69. Note the uniform striation count in the upper left hand potion of the photo. The variable amplitude loading is shown in Figure 70.

5.2 Baseline Spectrum B

The macro fracture face profile for specimen G270KB003-11-29 which was under the Spectrum B, variable amplitude loading, until fracture is shown in Figure 71. Note that there was secondary cracking on the non-EDM side with apparent crack nucleation sites at each corner of the opposite side of the bore merging to the middle of the thickness.

The SEM image in Figure 72 shows the location of the EDM notch side and the direction of crack growth for specimen G270KB003-11-29. The precracking zone for this specimen is shown in Figure 73 and Figure 74. The Figure 73-74 photos show a relative uniform striation versus the varied, but distinctly patterned photos for the variable amplitude areas in Figures 75-77. The photo in Figure 76 shows a 3D view of the crack growth front. The Spectrum B pattern can be seen in a repeated format in Figure 53. The overload zones mentioned in the Stephens et al. report and displayed in Figure 66 are shown in Figure 77.

5.3 Spectrum A + B Combination 1

The macrofracture face profile for specimen G270KB003-11-6 is shown in Figure 78. This specimen was under the Spectrum A+B Combination 1 loading, where the spectrum was switched from A to B at a bore crack length of 0.20 inches, until at least 100,000 EFH hours of loading was achieved. Note the semisymmetrical quarter elliptical crack front shape.

The SEM photo in Figure 79 shows location of the EDM notch side and the direction of crack growth for specimen G270KB003-11-6. The photo in Figure 80 shows the precrack zone with the uniform constant amplitude loading profile. Figures 81-83 show the transition zone at 0.20 inches in the bore in which the loading spectrum was switched from Spectrum A to Spectrum B at successive increased magnification. Figures 84-85 show different features from the fracture surface under the Spectrum B loading.

5.4 Spectrum A + B Combination 2

The macro fracture face profile for specimen G270KB003-11-31 is shown in Figure 86. This specimen was under the Spectrum A+B Combination 2 loading, where the spectrum was switched from A to B at a bore crack length of 80 percent of the part thickness, until at least 100,000 EFH hours of loading was achieved. Note the oblique through crack profile.

The SEM photo in Figure 87 shows location of the EDM notch side and the direction of crack growth for specimen G270KB003-11-31. The photo in Figure 88 shows the precrack zone with the uniform constant amplitude loading profile. Figure 89 shows the Spectrum A zone crack growth front and Figure 90 shows the crack growth front for the Spectrum B zone. Note the inclusion particles in Figure 90.

5.5 Spectrum A + B Combination 3

The macro fracture face profile for specimen G270KB003-11-13 is shown in Figure 91. This specimen was under the Spectrum A+B Combination 3 loading, where the spectrum was switched from A to B when the bore crack grew through the part thickness, until at least 100,000 EFH hours of loading was achieved. Note the oblique through crack profile.

The SEM photo in Figure 92 shows the precrack zone with the uniform constant amplitude loading profile for specimen G270KB003-11-13. Figure 93 shows the Spectrum A zone crack growth front and Figure 90 shows the crack growth front for the Spectrum B zone. Note the repeated striation pattern in Figure 94.

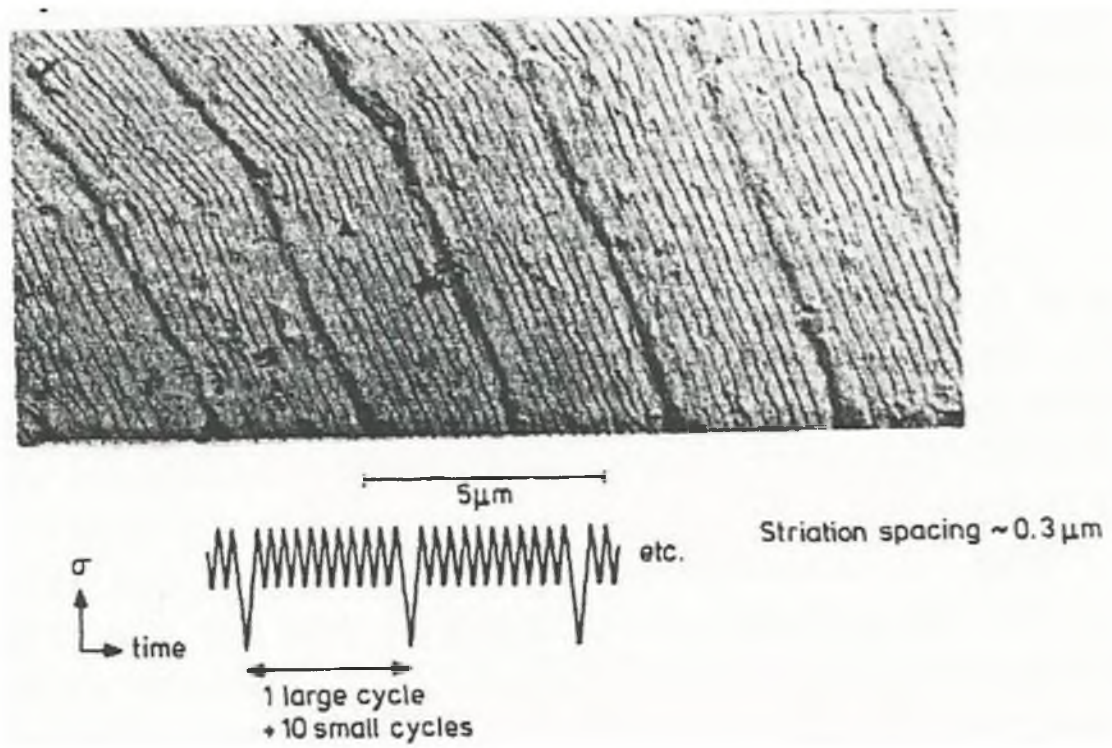


Figure 64 Correspondence Between Striations and Load Cycles in Al-Alloy Sheet

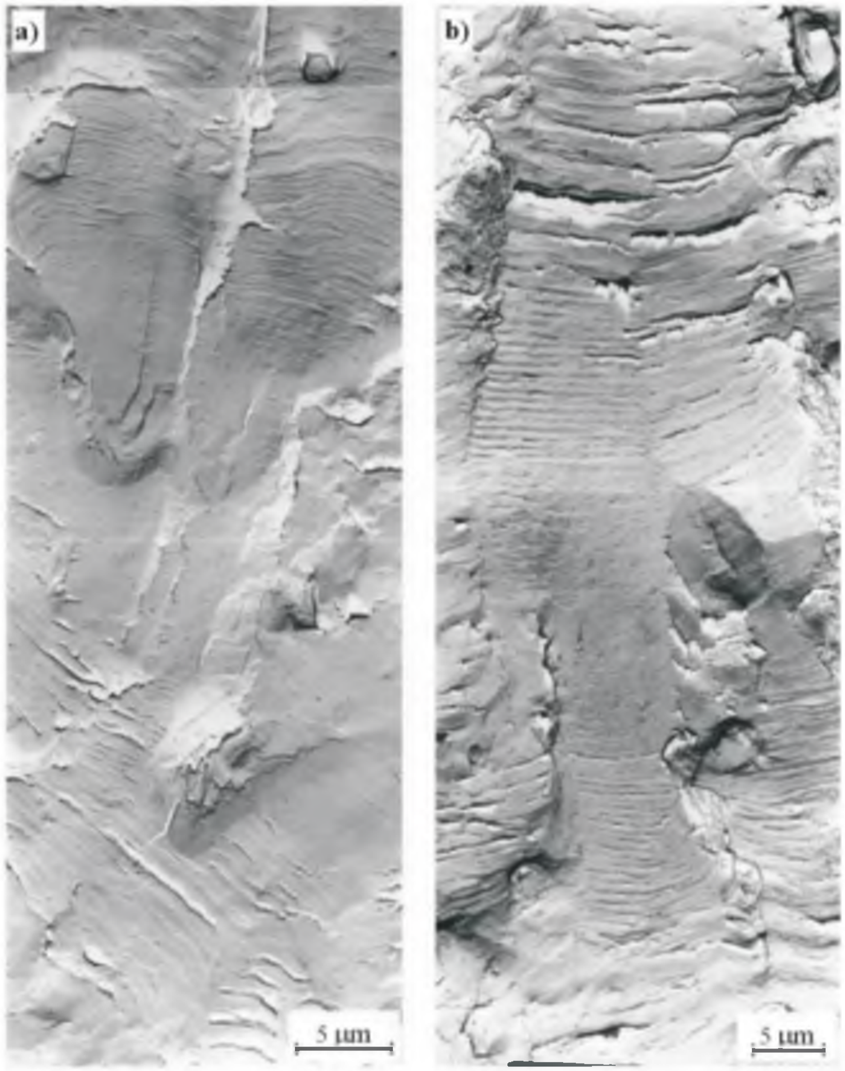


Figure 65 Patterns of Fatigue Striations on the Fracture Surfaces of 2024-T3 Alloy LT Specimens. Fig (a) Sows the Crack Front Under the Variable Amplitude Loading versus (b) Precrack Front Under Constant Amplitude Loading

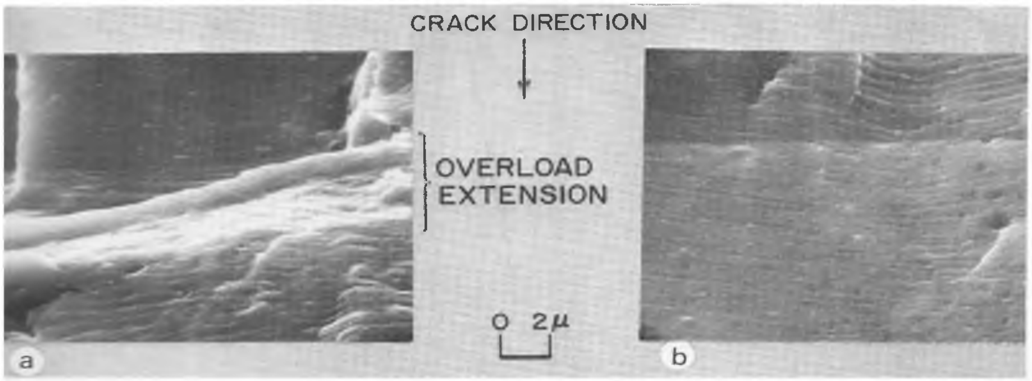


FIG. 9—*SEM fractographs indicating delayed retardation following tensile overload in 2024-T3 aluminum; OLR = 2.5, R = −1/2; (a) overload region and (b) 0.13 mm after overload.*

Figure 66 SEM Fractographs Indicating Delayed Retardation Following Tensile Overload in 2024-T3 Aluminum: (a) Overload Region and (b) 0.13 mm After Overload[46]

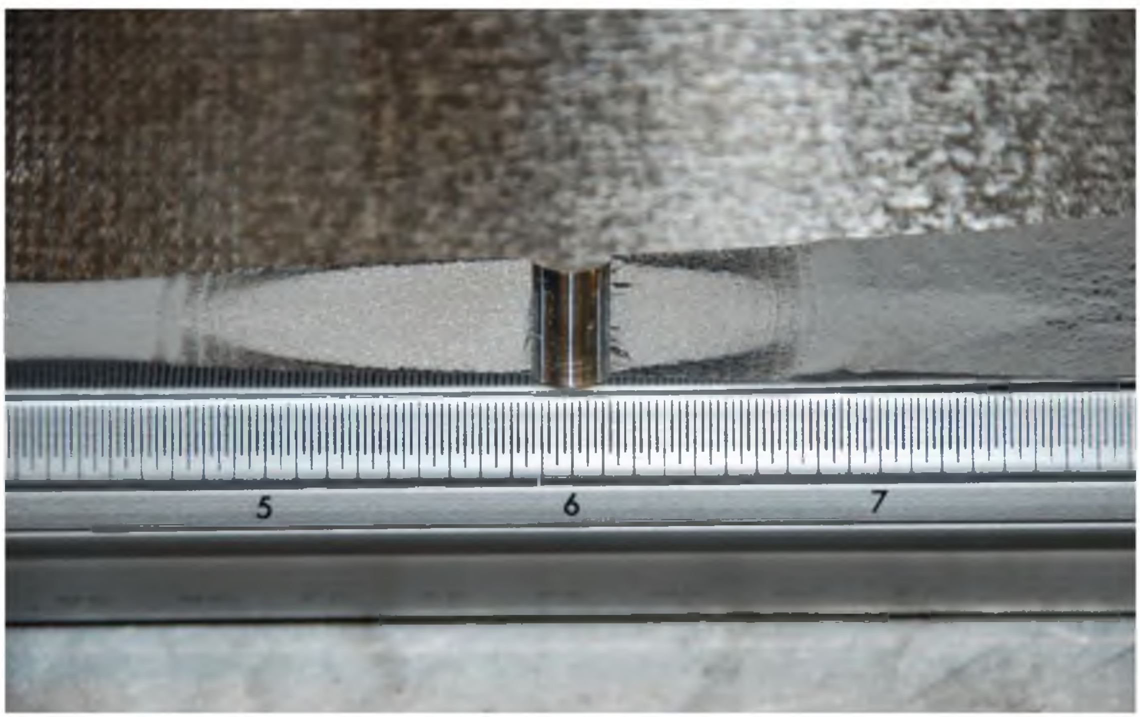


Figure 67 Sample GT270KB003-11- 4 – Spectrum A

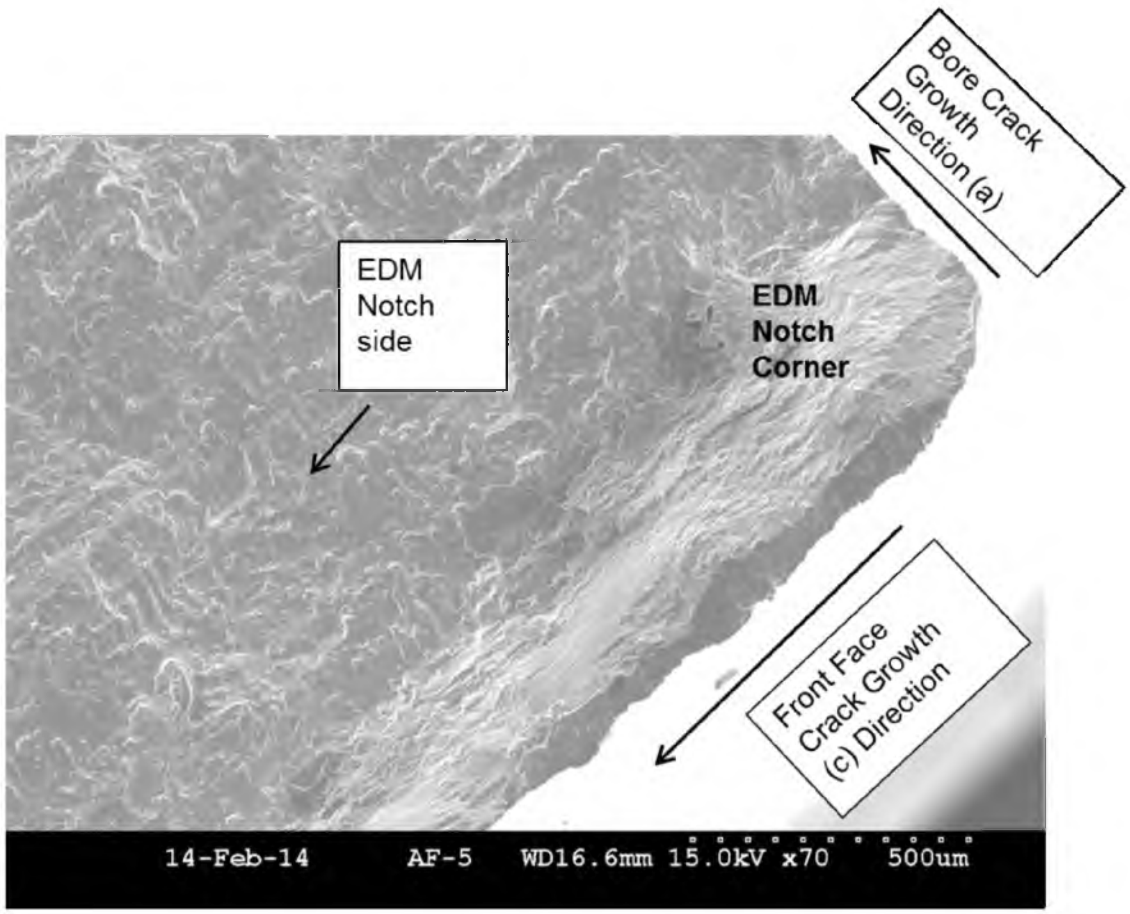


Figure 68 Sample GT270KB003-11- 4 – Magnification Level at 70X – Spectrum B Combination (Tensile/Compression Load Direction Out of Page)

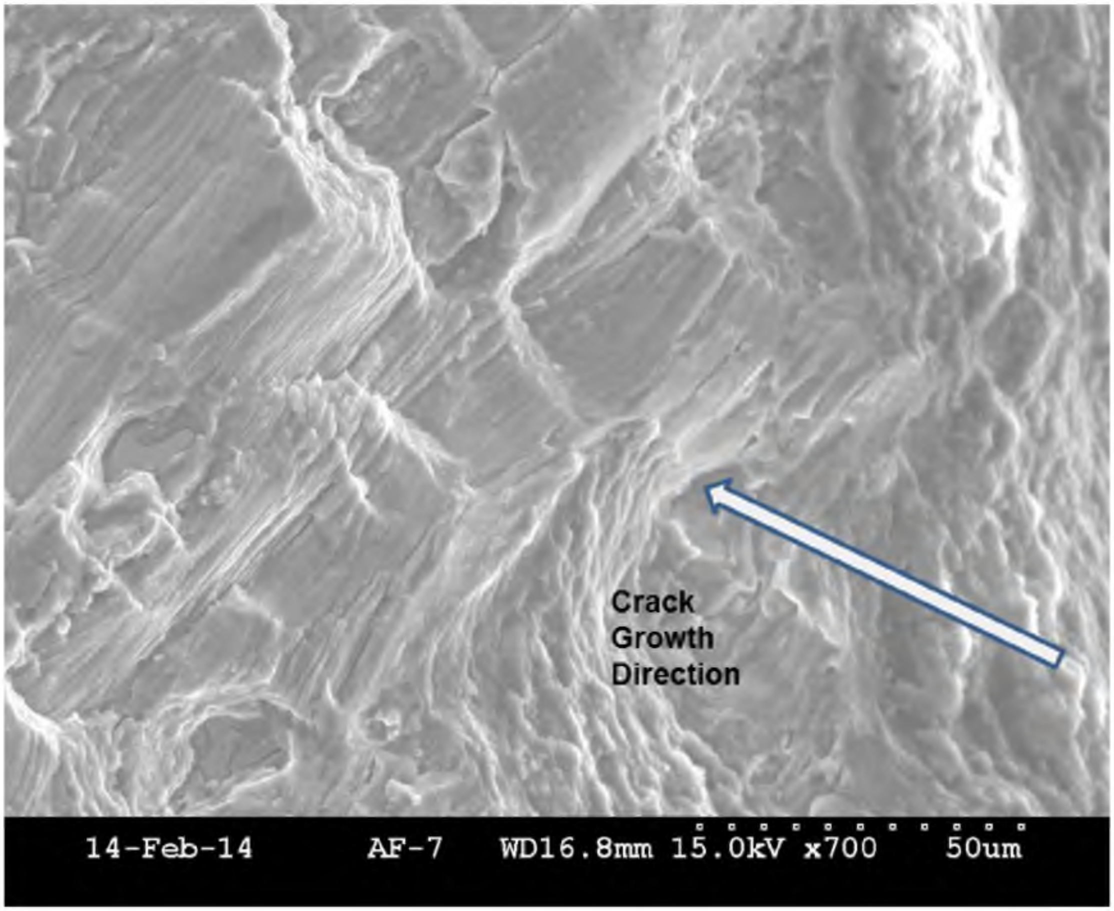


Figure 69 Precracking Area of Sample GT270KB003-11- 4 - Spectrum A Baseline x700 Magnification

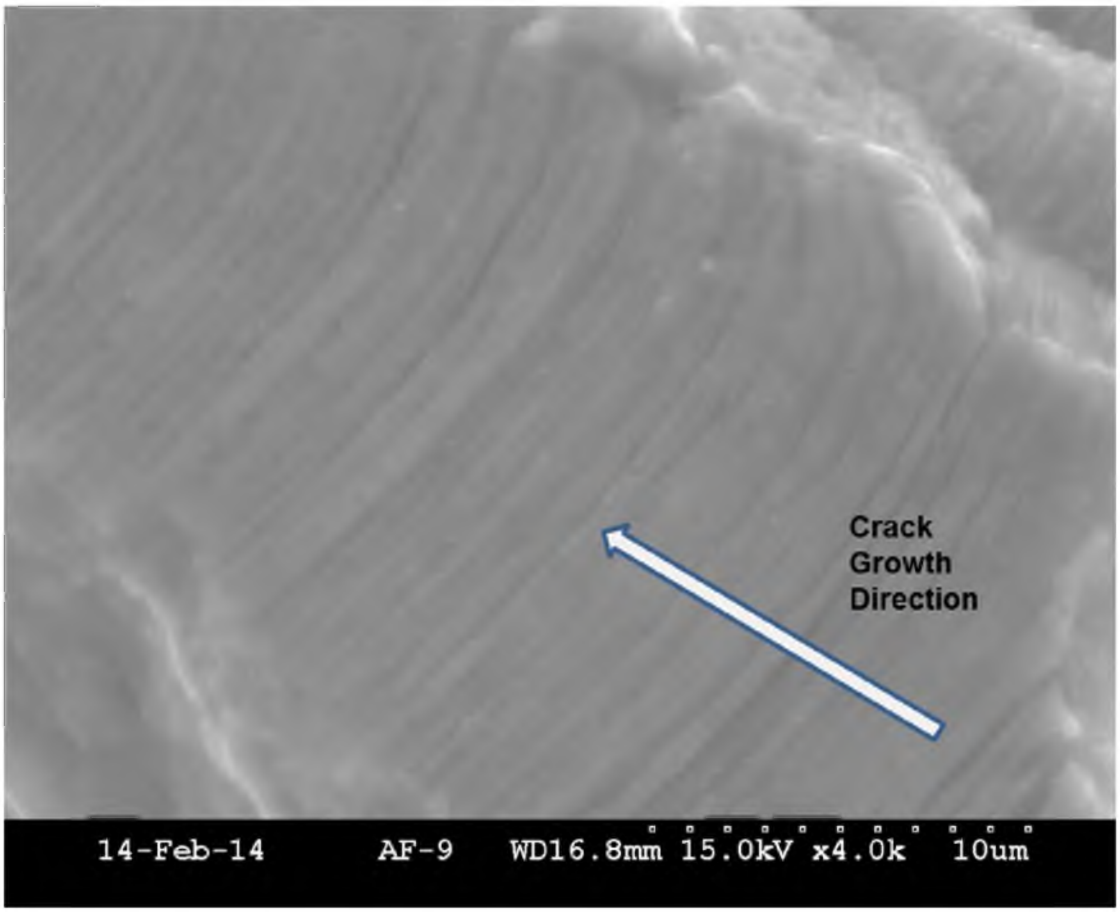


Figure 70 Specimen GT270KB003-11-4 Crack Growth Front in Spectrum A Zone

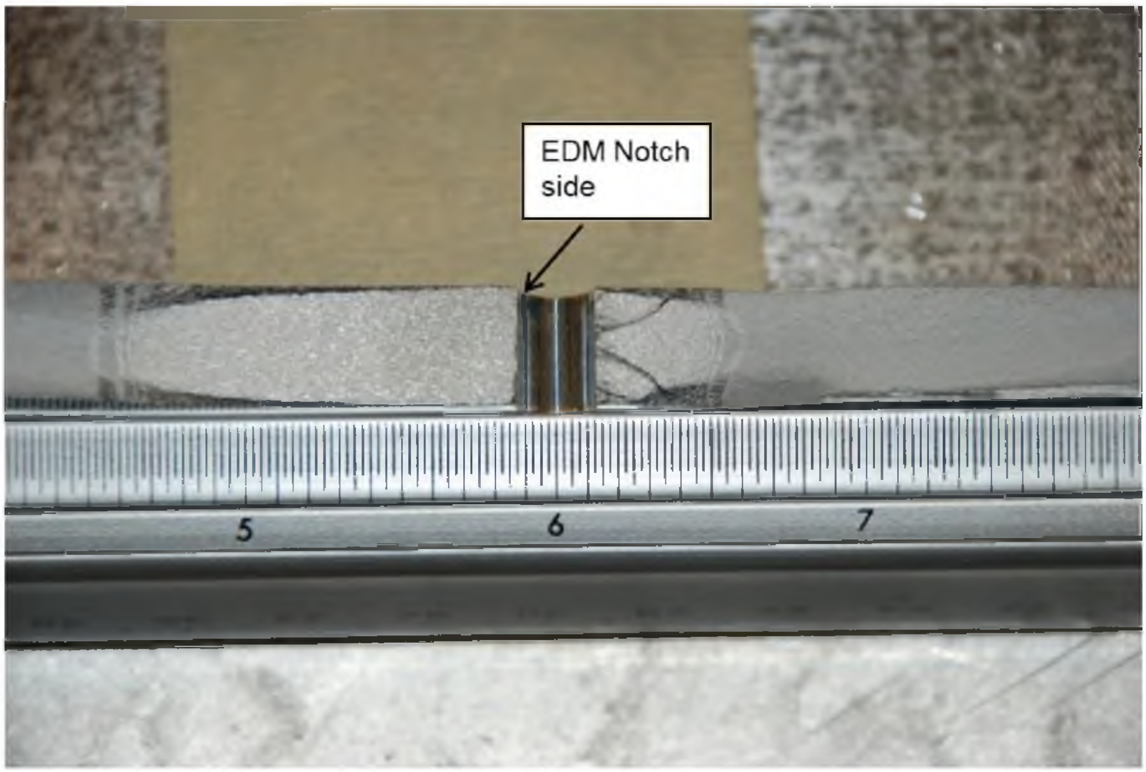


Figure 71 Sample GT270KB003-11- 29 Spectrum B Baseline Loading

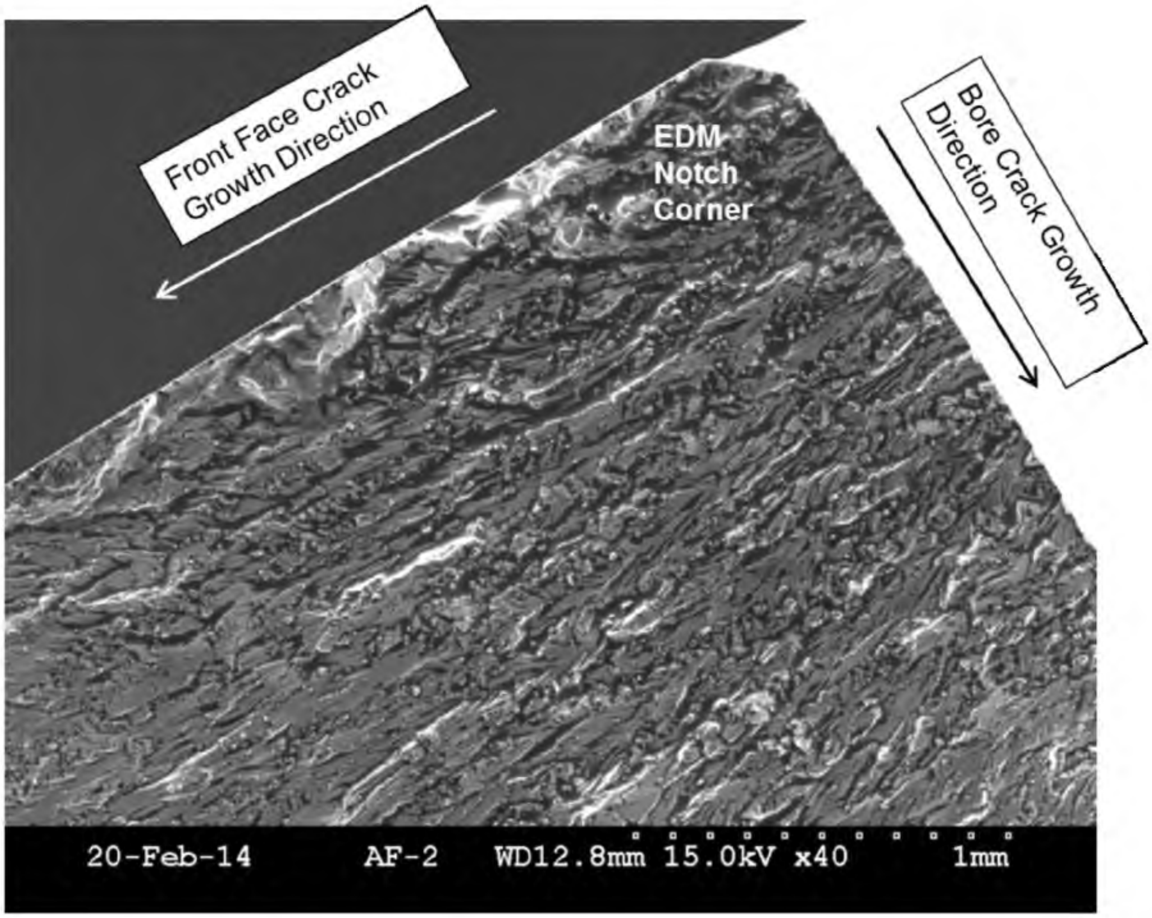


Figure 72 Sample GT270KB003-11- 29 – Spectrum B - Precracking Area at 40X – Loading and LT Direction Out of the Page

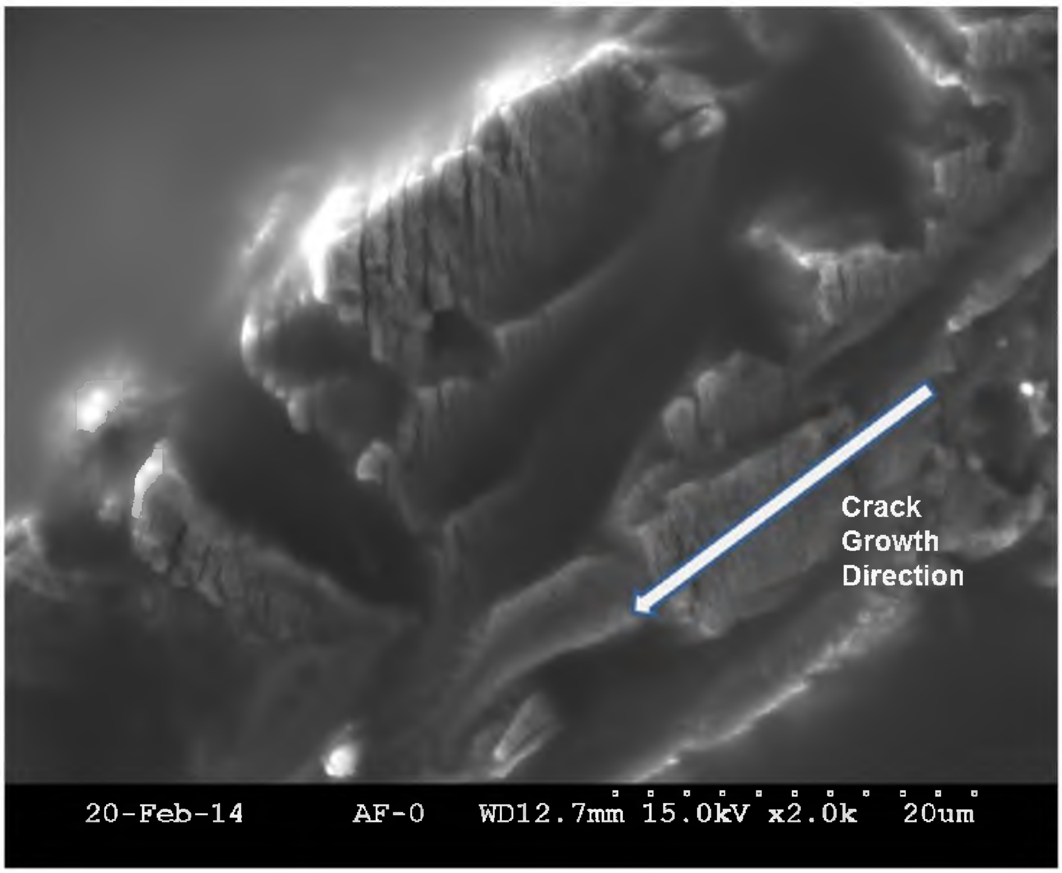


Figure 73 Sample GT270KB003-11- 29 **Precrack Zone Showing Uniform Striations – Magnification at 2000X**

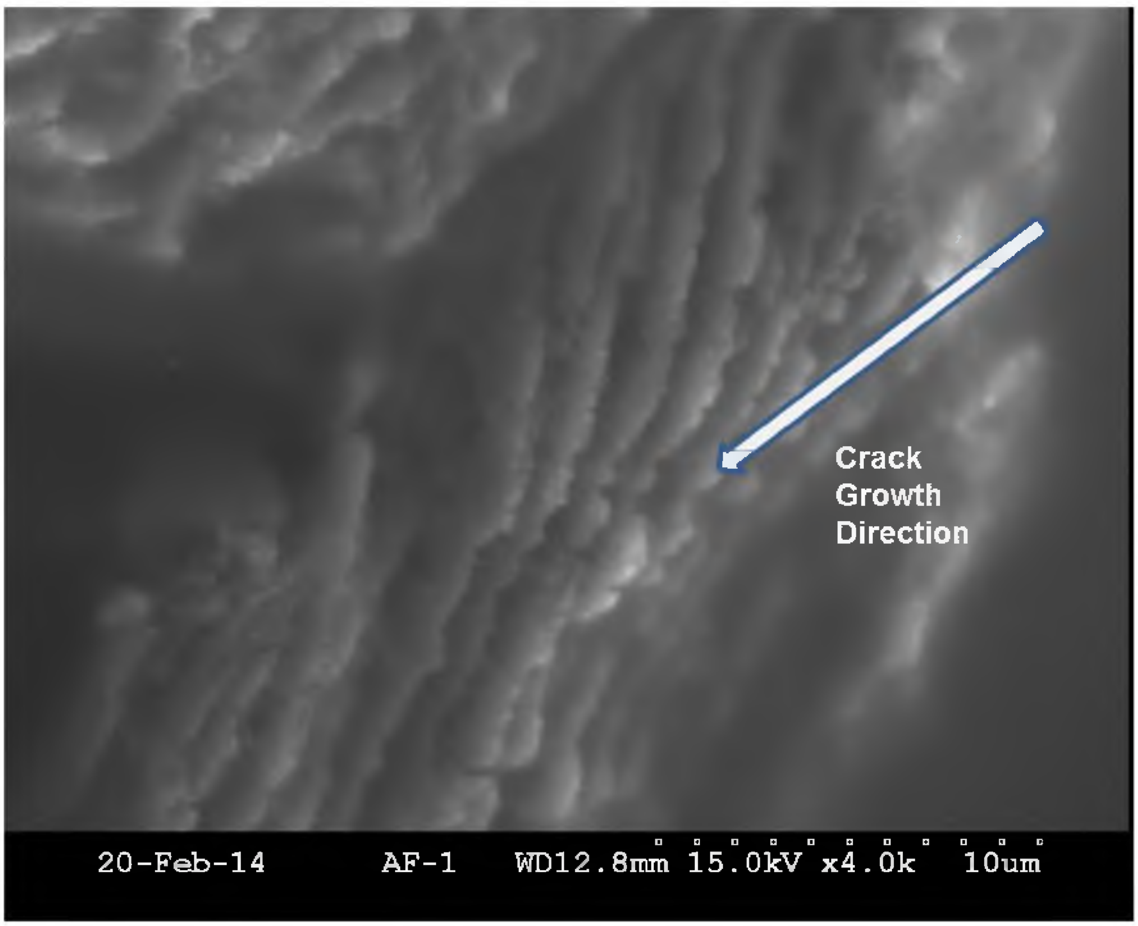


Figure 74 Sample GT270KB003-11- 29 – Spectrum B – Precrack Area at 4000x Magnification

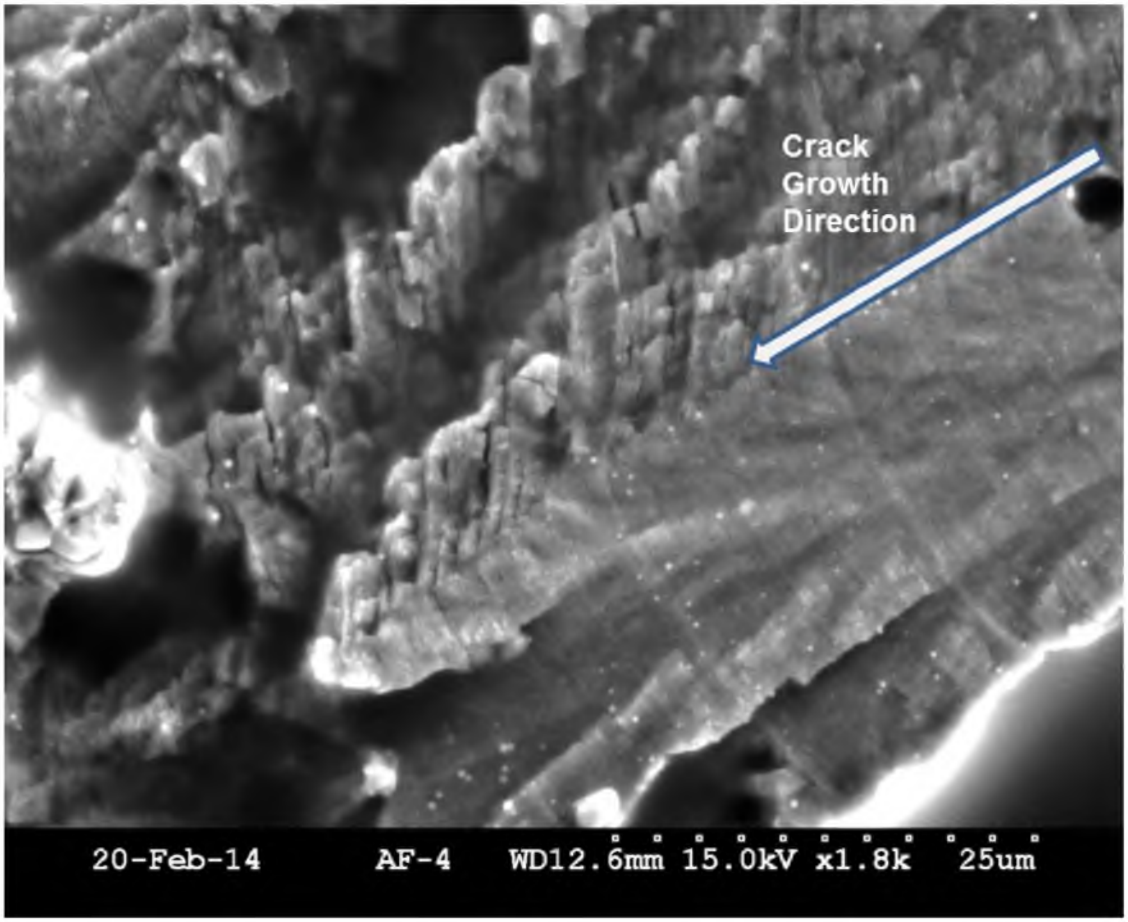


Figure 75 Sample GT270KB003-11- 29 B Spectrum Zone at 1800X Magnification

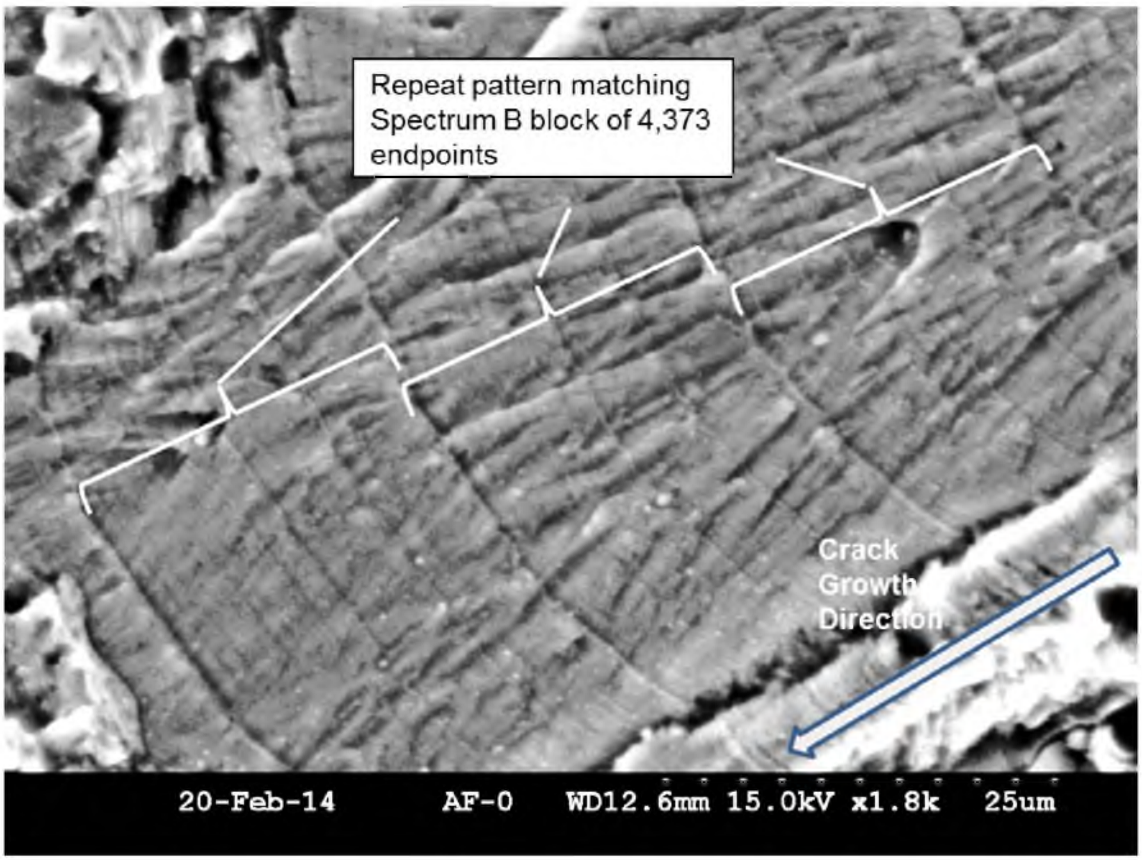


Figure 76 Sample GT270KB003-11- 29 Striation Pattern at 1800X Magnification

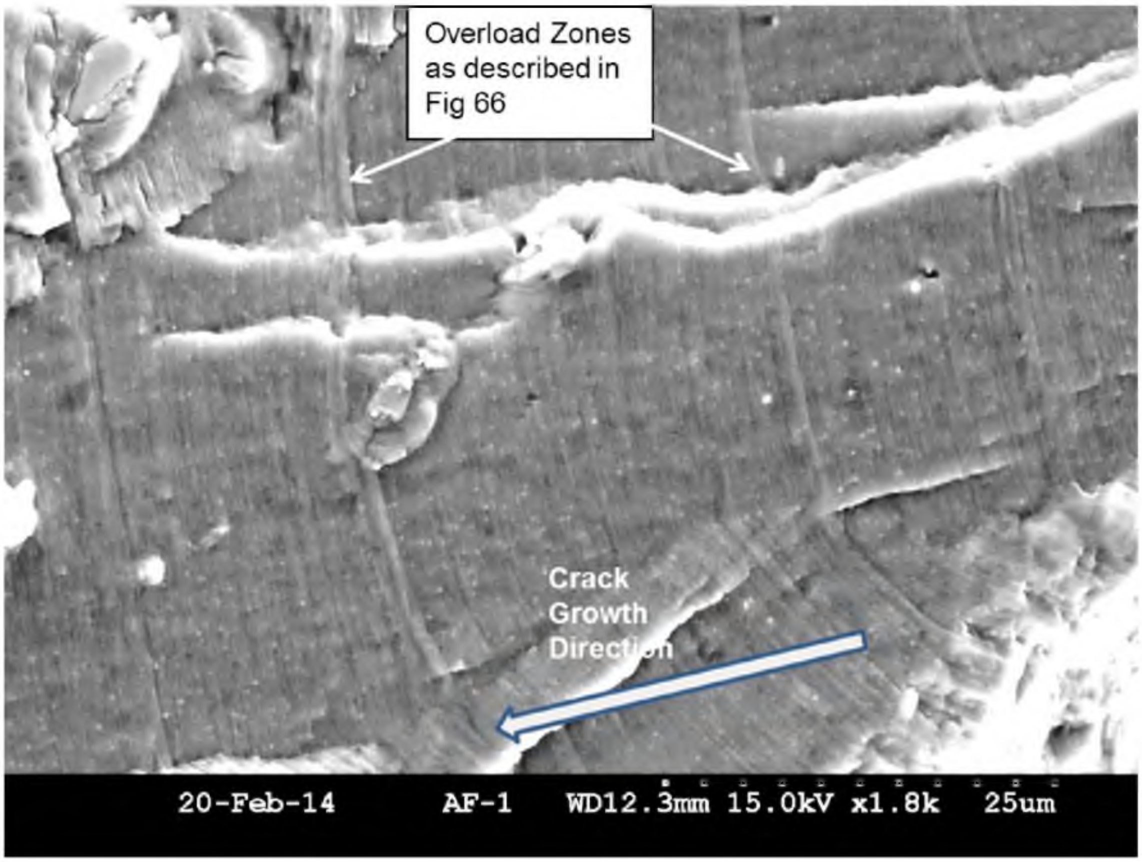


Figure 77 Sample GT270KB003-11- 29 Variable Amplitude Overloads Similar to Those Shown in Figure 66

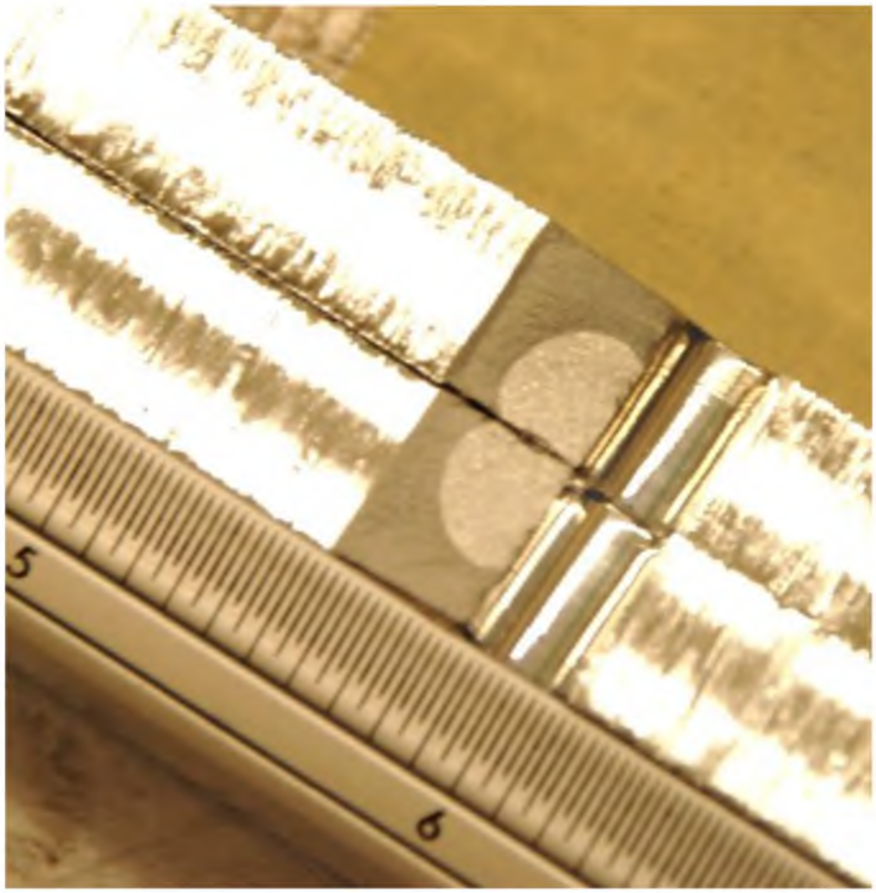


Figure 78 Macrofracture Face Profile for Specimen G270KB003-11-6 Spectrum A+B Combination 1

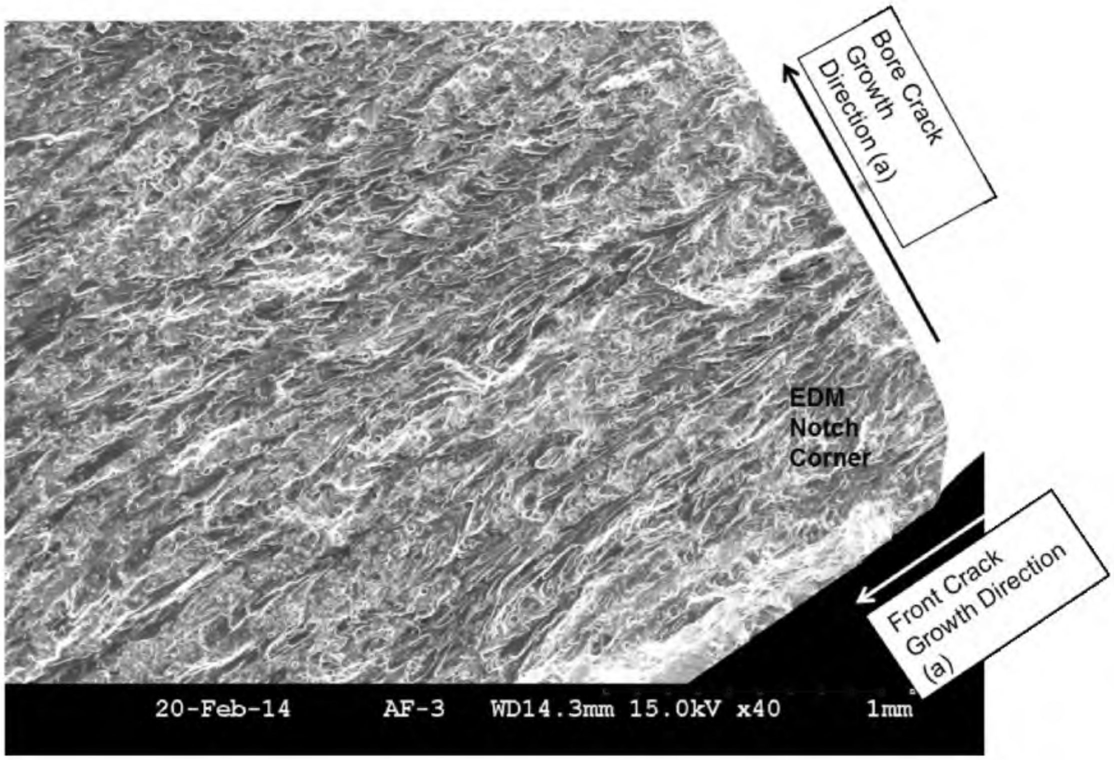


Figure 79 G270KB003-11-6 Precrack Zone

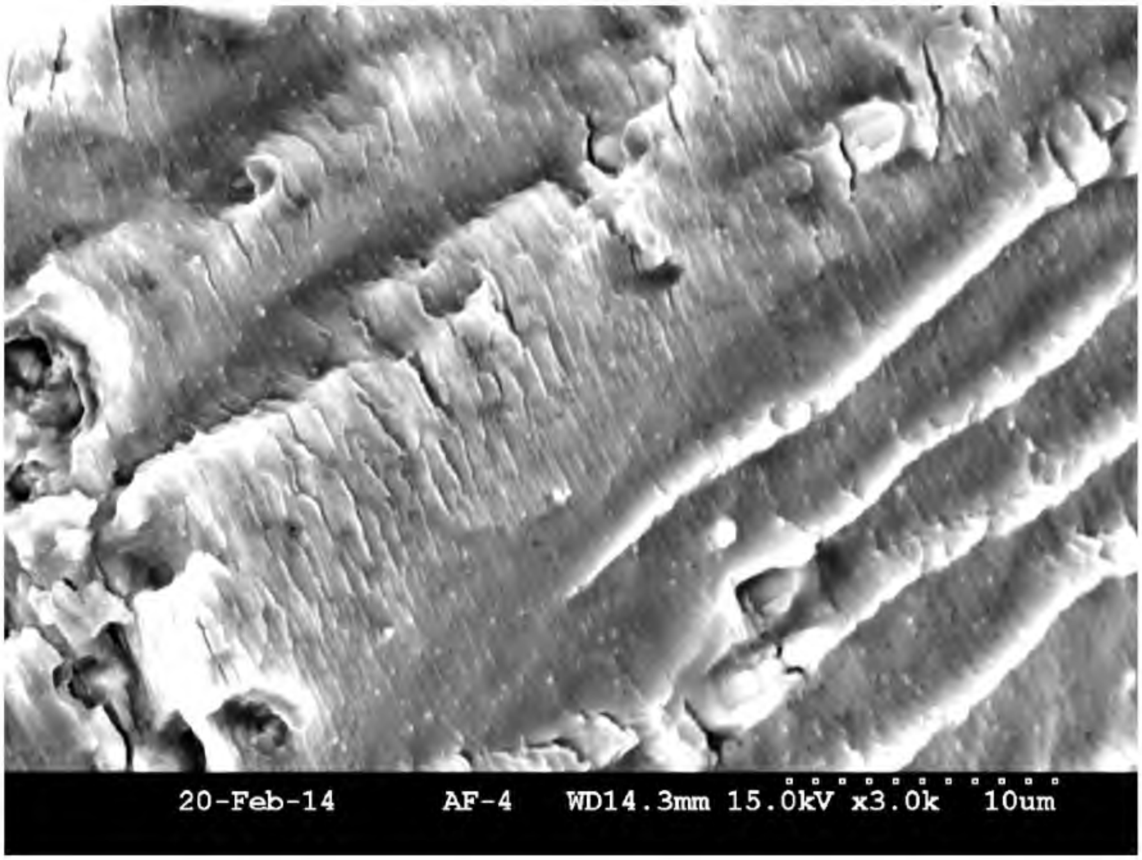


Figure 80 Sample GT0KB003-11-6 Precrack Striations at 3000X Magnification

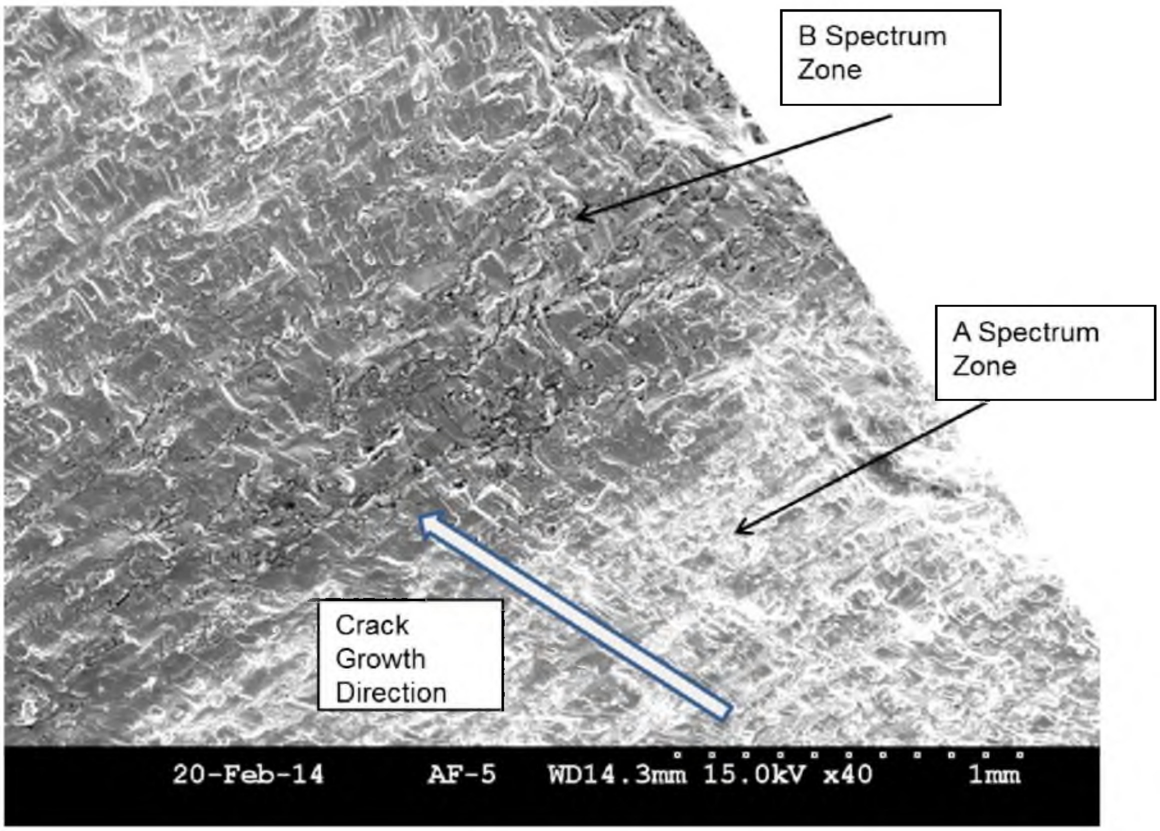


Figure 81 Sample GT0KB003-11-6 - Transition from Spectrum A to Spectrum B at the 0.20 inch Point on the Bore

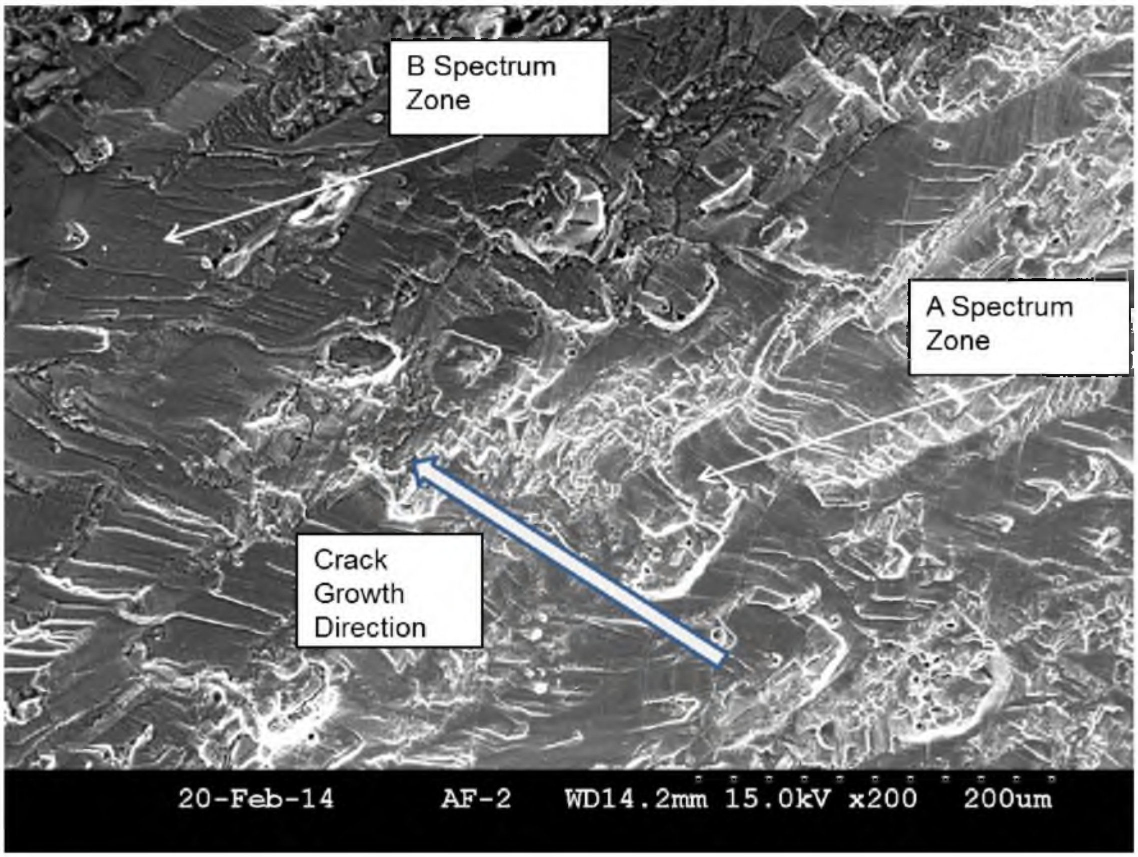


Figure 82 Sample GT0KB003-11-6 Same Area as Figure 81 but at 200x Magnification

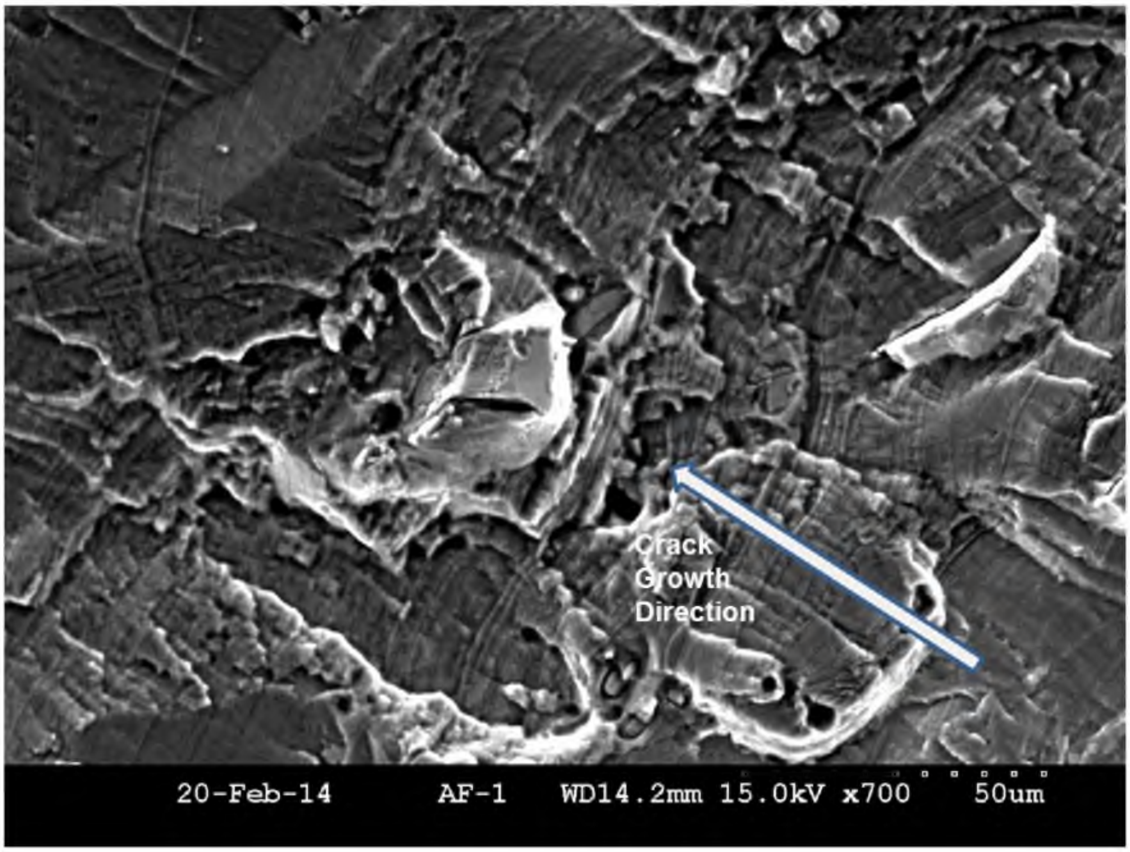


Figure 83 Sample GT0KB003-11-6 Same Area as Figures 81 and 82 but at 700x Magnification

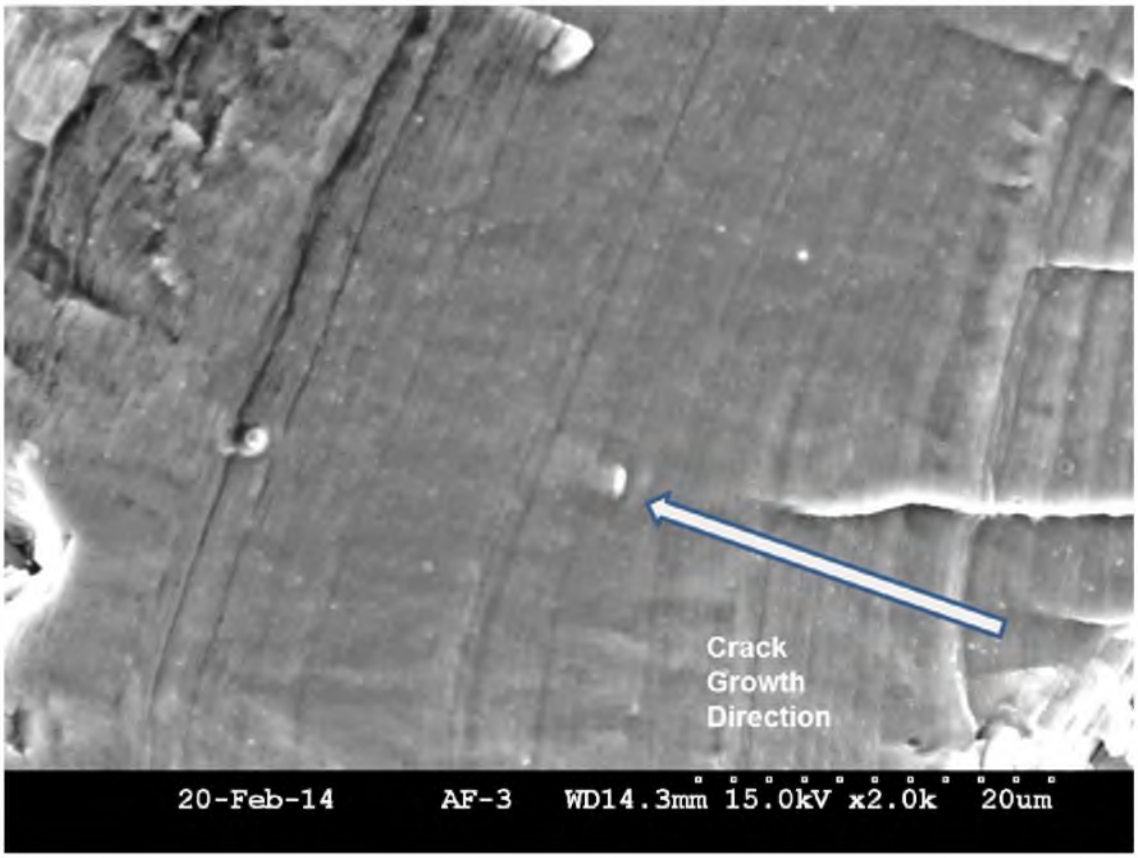


Figure 84 Sample GT0KB003-11-6 Spectrum A Zone Crack Growth Front

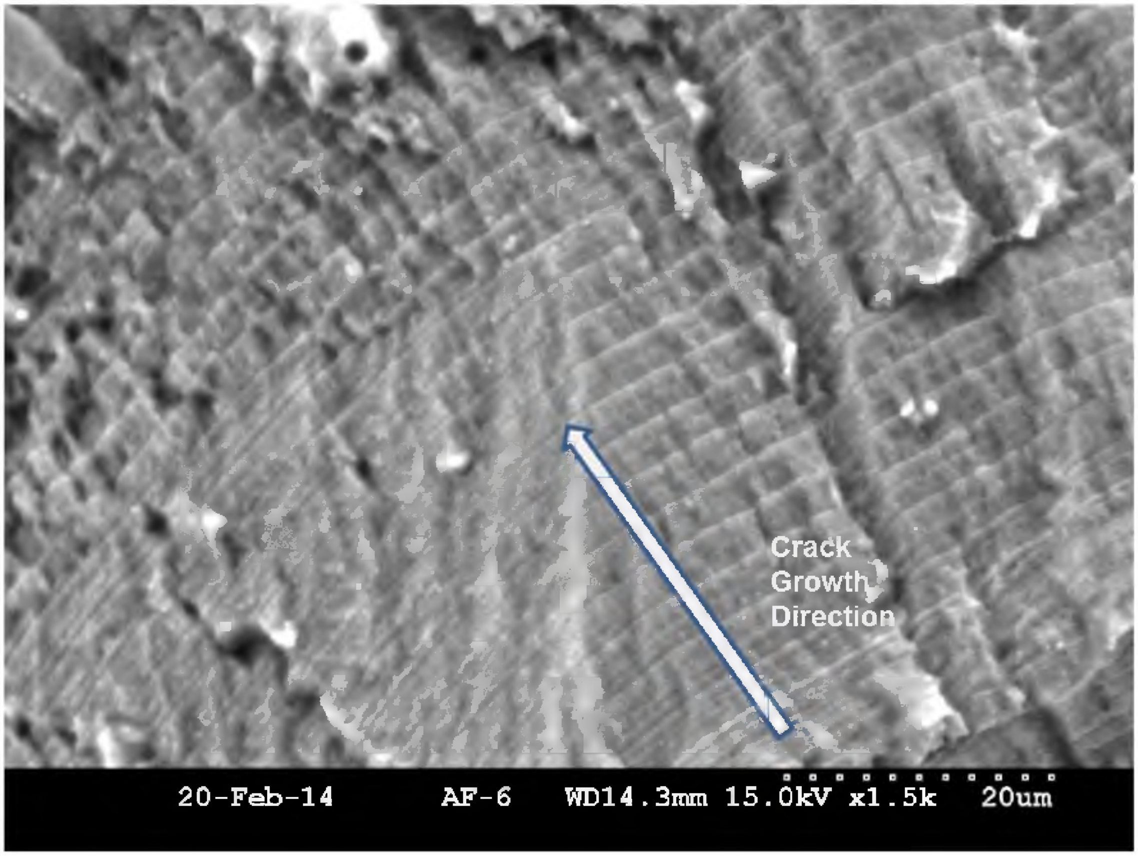


Figure 85 Sample GT0KB003-11-6 Spectrum B Zone Crack Growth Front

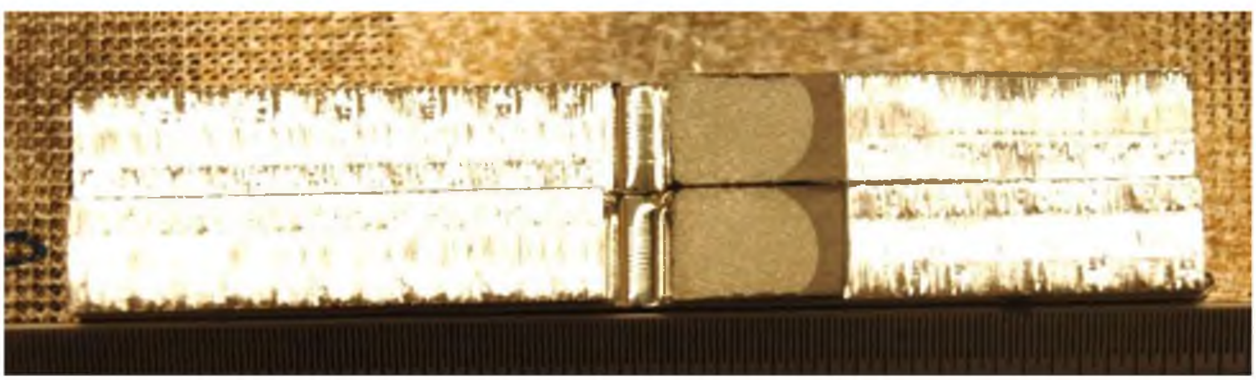


Figure 86 GT0KB003-11-31 Spectrum A+B 2 Combination

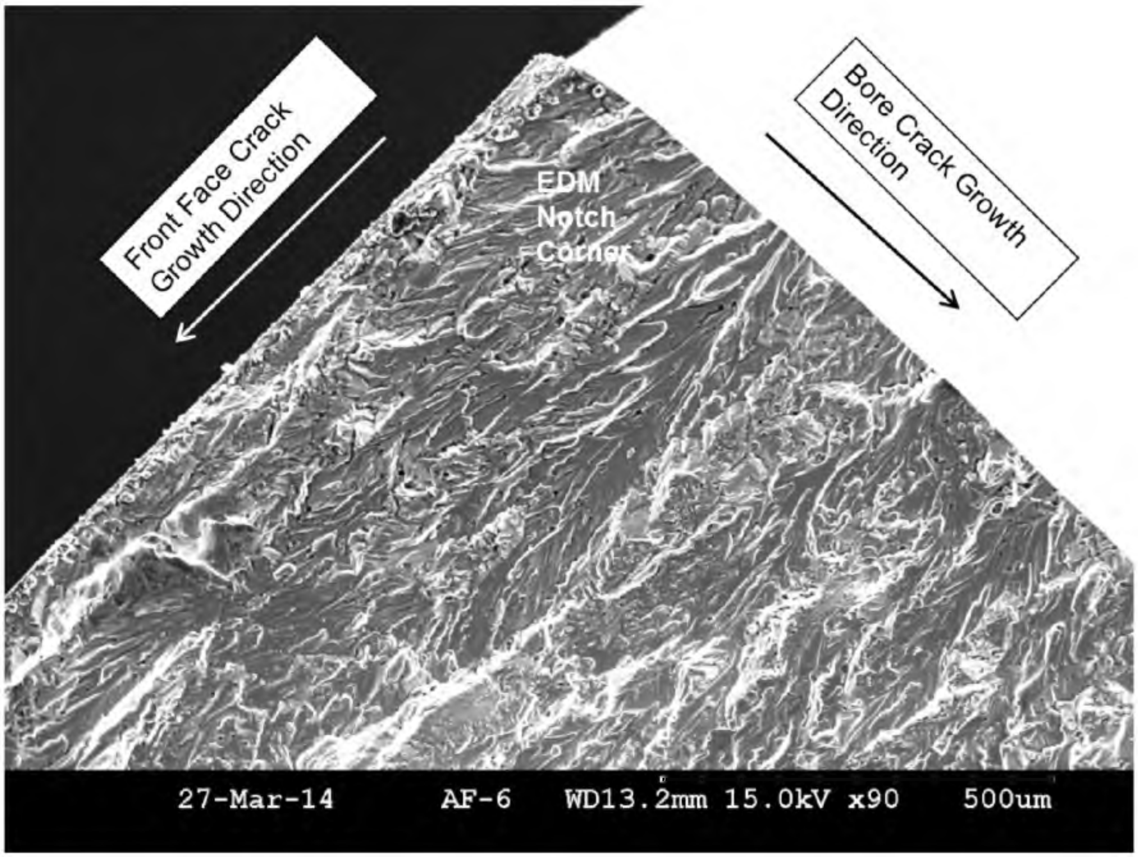


Figure 87 Sample GT0KB003-11-31 Precrack Zone

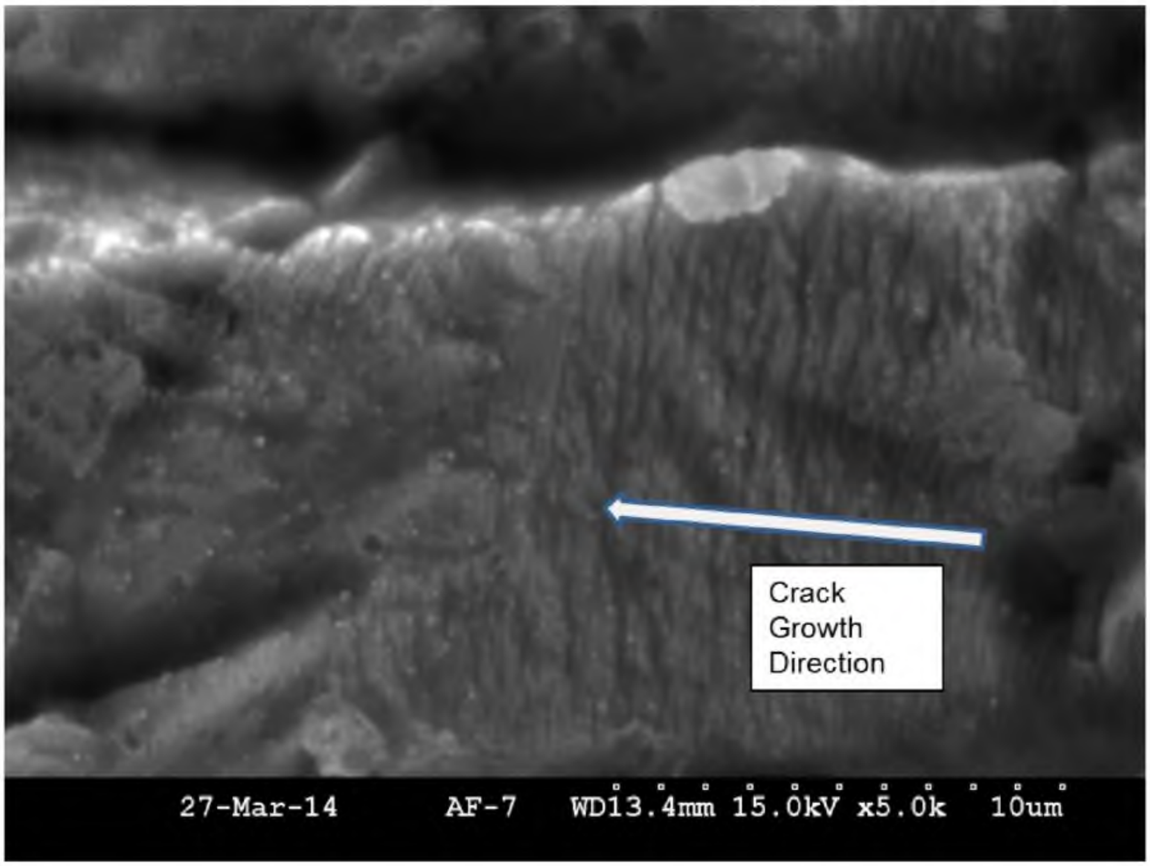


Figure 88 Sample GT0KB003-11-31 Precracking Striations

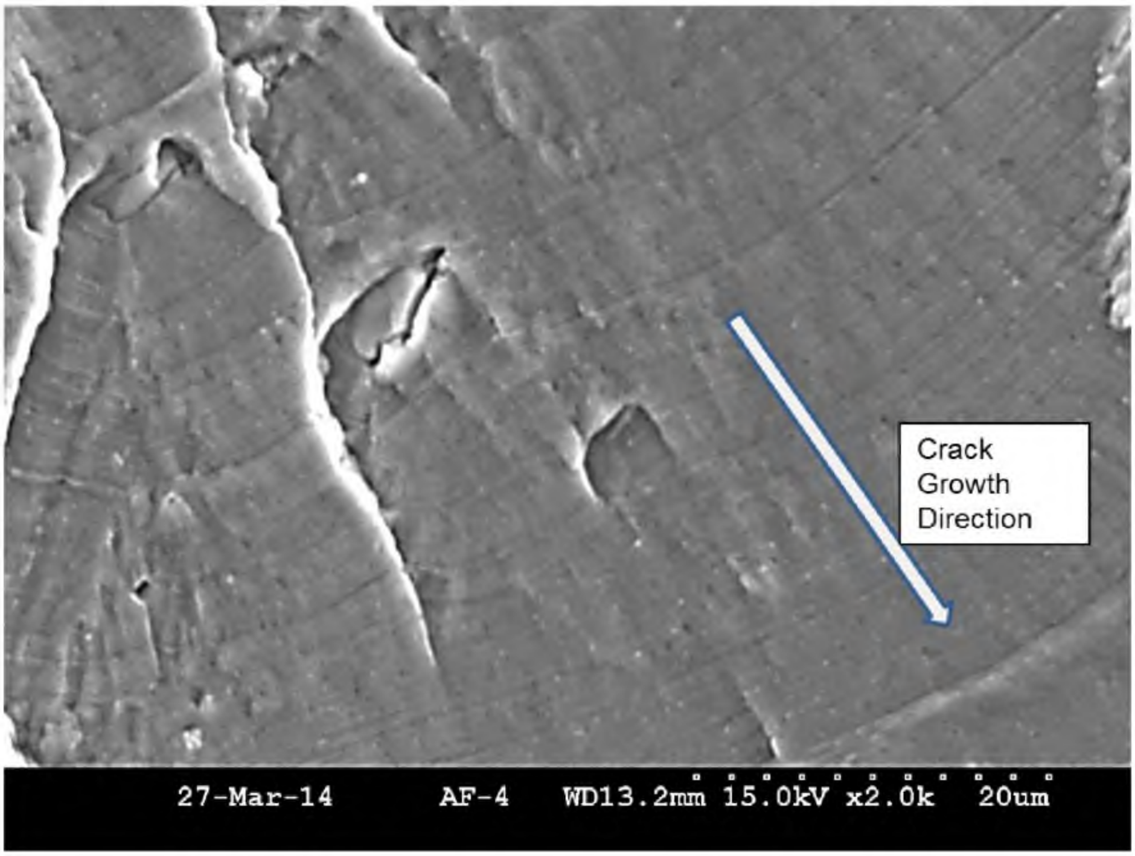


Figure 89 Sample GT0KB003-11-31 Spectrum A Zone Crack Growth Pattern

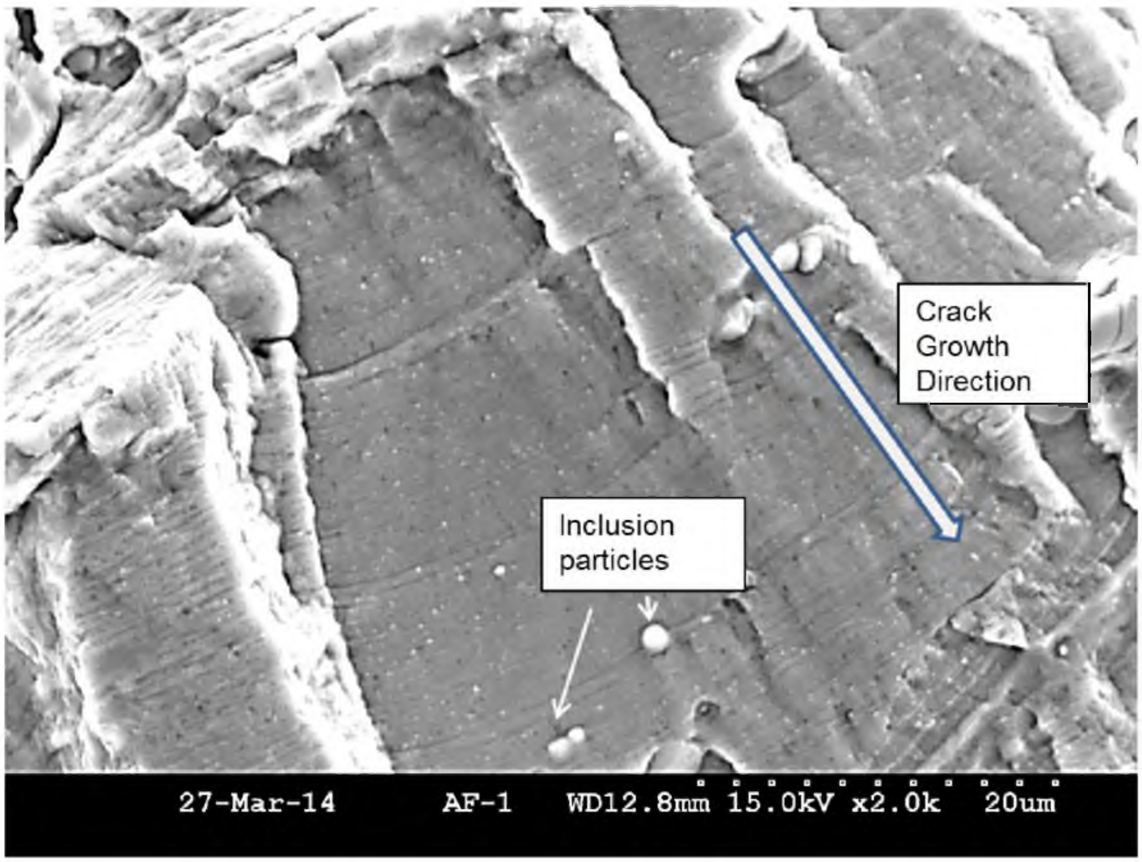


Figure 90 Sample GT0KB003-11-31 Spectrum B Zone Crack Growth Pattern

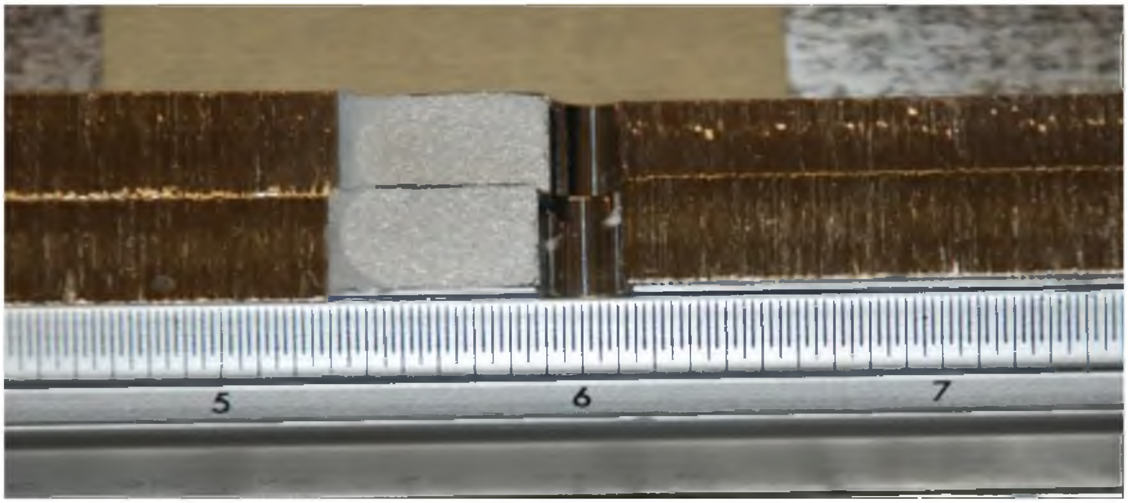


Figure 91 Specimen G270KB003-11-13 Spectrum A+B Combination 3

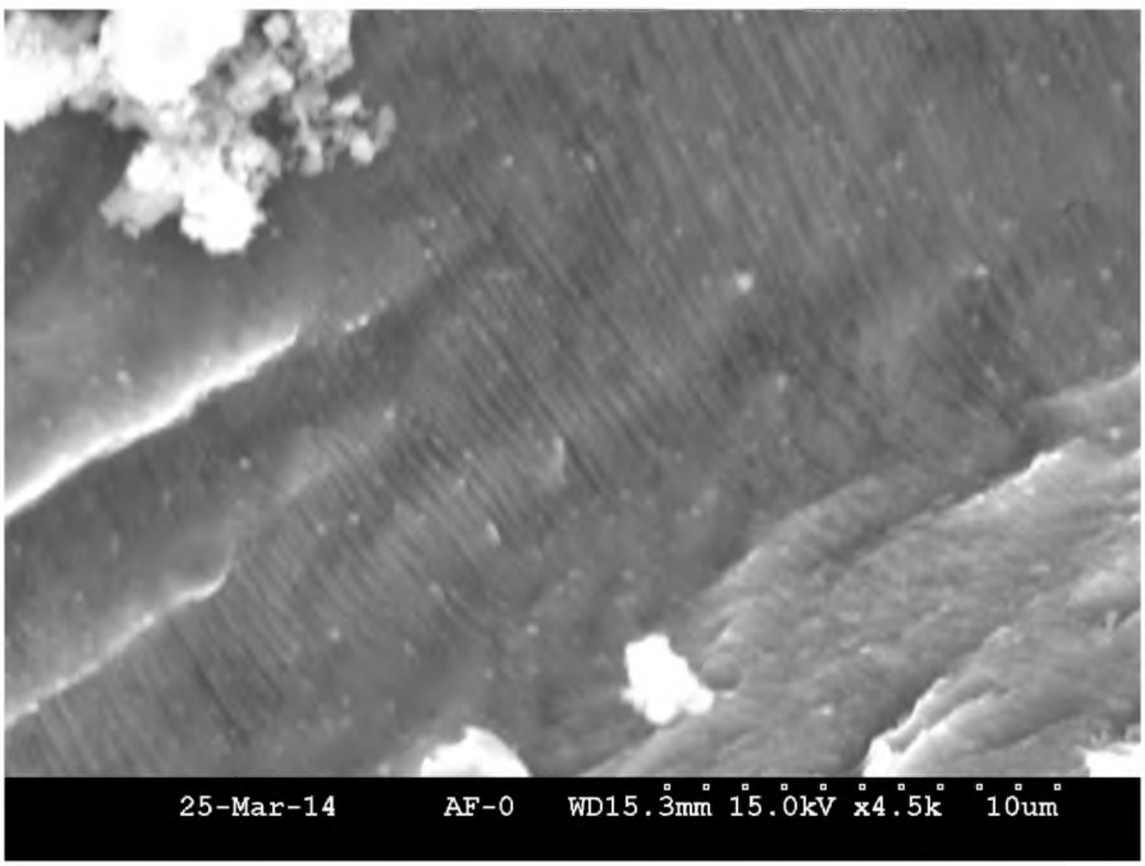


Figure 92 Specimen G270KB003-11-13 Precracking Striation Pattern

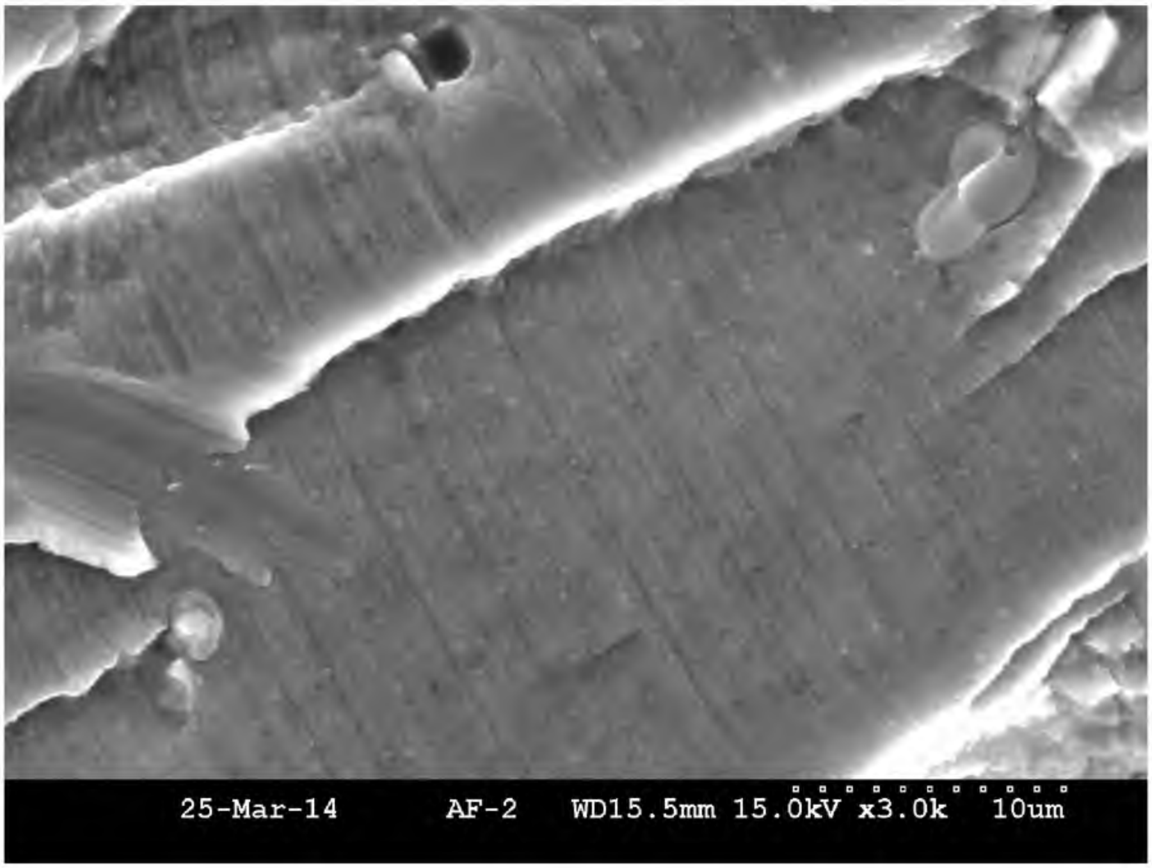


Figure 93 Specimen G270KB003-11-13 Spectrum A Loading Zone

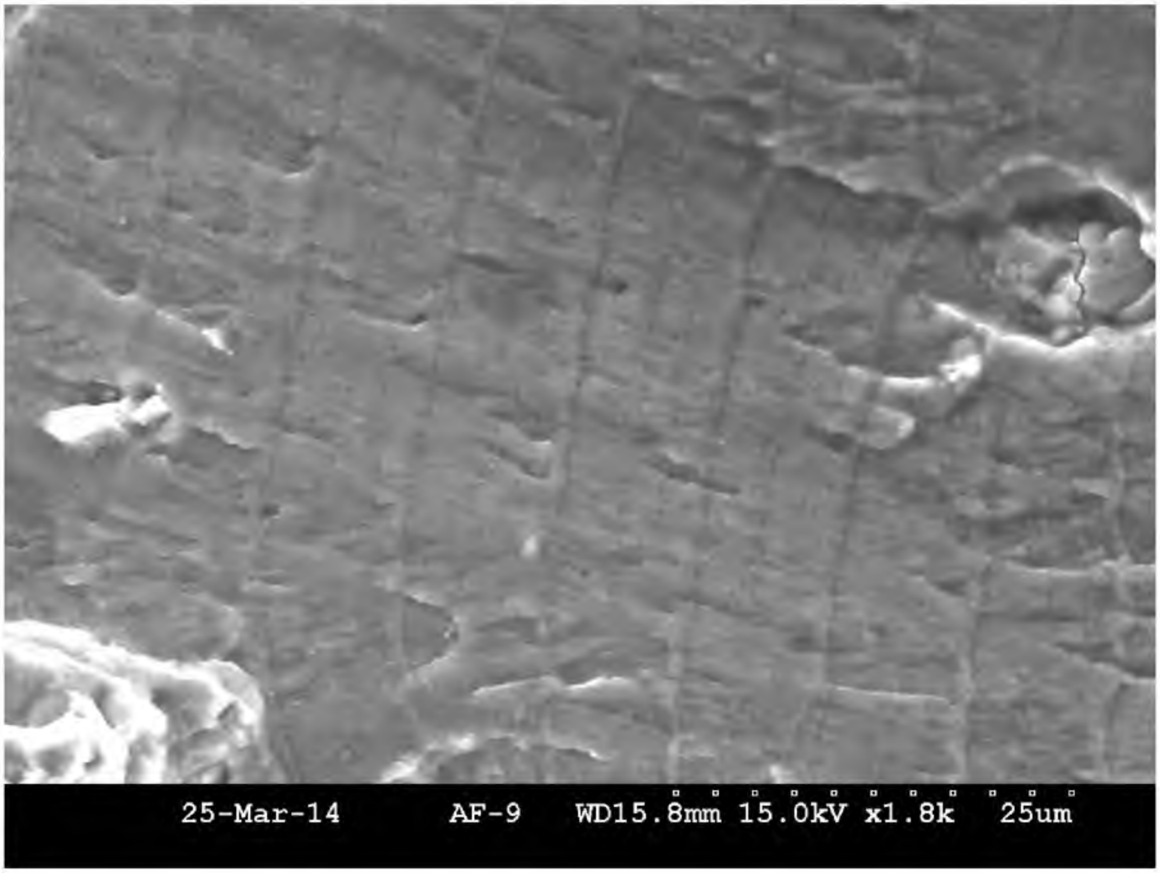


Figure 94 specimen G270KB003-11-13 Spectrum B Zone Striation Pattern

CHAPTER 6

SUMMARY

6.1 Conclusions

The overarching goal of this research was to obtain life predictions for 5 different spectrum loading combinations and provide the necessary justification to allow for maintenance schedule modification when temporary usage environments are encountered. A secondary goal is to provide useful data on crack tip plasticity and retardation to the fatigue and fracture community. Trying to achieve both goals to the fullest extent is beyond the scope of this effort and further research with a detailed process is necessary for fully characterizing the crack tip plasticity and retardation.

The methodology of fatigue testing representative specimens under the exact loading spectra and assessing the changes in loading on the material response at various fatigue life points is highly effective as long as all of the load frame and associated hydraulic and cooling system are fully functional. The evaluations were possible largely due to the previous fatigue crack growth data and modeling accomplished for this 2024-T351 material and for the geometry used in the experiment. For new materials and geometry configurations, sufficient fatigue growth modeling will need to be established using E647 guidelines as a reference.

This experiment showed a significant increase in inspection interval which provides economic savings while maintaining the same levels of safety of flight. Retardation models were developed for all scenarios except the Spectrum A+B Combination 3 scenario which would benefit from further research based on my Recommendations section.

6.2 Significance

This experiment contributes to the field of fatigue and fracture mechanics by developing a methodology to assess the material response effect of various spectrum combinations. It provides the analyst the ability to assess actual spectrum loading conditions and update damage tolerance life prediction models for a change in spectrum loading. This provides the structural engineer and analyst working on a product in service the ability to assess the change in loading environment that should be reflected in a change to the inspection interval. This is very beneficial for military aircraft that are deployed and loaded under a benign spectrum, in that the maintenance inspection interval can be adjusted to allow for keeping the aircraft longer in theatre without bringing it back for NDI of critical fatigue locations. Furthermore, this method allows for characterizing the residual strength condition when the aircraft is returned to the original loading condition upon rotating out of theatre missions to stateside training. For the designer, this method allows for analyzing the effect of several spectrum options for material selection and for life prediction models.

6.3 Recommendations

1) It was an important lesson learned in this research that to conduct an effective fatigue crack growth study, the entire system needs to be understood and functioning. This system includes the hydraulic system, the cooling system, electrical power supply, load frame and controller system and software which need to be considered and evaluated for suitable service. It is highly recommended that adequate time be spent to ensure Quality Control steps be established for the entire system.
2) Acquire or develop cameras, still or video, that can be incorporated into the travelling microscope to capture focused images of the crack front for reporting purposes.
3) Conduct further research with an expanded matrix to develop the life limit in which a change in spectrum shows no impact. This research should involve running the coupons to full fracture to better estimate the retardation effects.
4) Conduct further micro research using the SEM to characterize the local retardation effects due to overloads and underloads.
5) Include more replicates per combination based on Design of Experiments to assess the variability of the process.
6) Upgrade AFGROW modelling to allow load history and plastic zone effect to transfer from one spectrum loading profile to another.
7) If a product is expected to experience temporary changes in loading environment that are on the order of 10% of the total expected service

objective or greater, provisions should be made to assess these environments in the context of maintenance scheduling.

APPENDIX A

TEST SPECIMEN MATERIAL CERTIFICATION SHEETS

Aero Specialties Material Corp.
20 Burt Drive
Deer Park, NY 11729
USA

Voice: 631-242-7200
Fax: 631-242-7652

PACKING SLIP

Invoice Number: 15540
Invoice Date: Oct 23, 2012
Page: 1

Sales Order Number: N5090-DL

Bill To:	Ship to:
NORTHROP GRUMMAN 925 SO. OYSTER BAY ROAD M/S U03-26 BETHPAGE, NY 11714	NORTHROP GRUMMAN TECH SVC. 925 SOUTH OYSTER BAY ROAD ATT: KEVIN COOK BETHPAGE, NY 11714

Customer ID	Customer PO	Sales Order
NORTHR	TA2086004	N5090-DL
Sales Rep ID	**Shipping Method**	**Payment Terms**
DONNA	ROBLIS	Prepaid

Order Qty	Item	Item Unit	Description	Shipped Qty
40.00	2024-T351 .500"THK.	EA	2024-T351 QQA-250/4 .500 X 4.250" X 16.250" GRAIN W/16.250" DIM	40.00
1.00	PO#	<Each>	LOT# 566454A5	1.00
1.00	FREIGHT CHGS	<Each>	FREIGHT CHARGES PREPAID ON THE ABOVE REFERENCED PO.	1.00

Certificate of Compliance

his is to certify that the material supplied against the above purchase order has been produced in accordance with applicable specifications.

D. Anla

Certification Clerk

AERO SPECIALITIES CERTIFY THIS IS
A TRUE COPY OF THE MILL TEST
REPORT - USED TO FILL YOUR ORDER.
Company Northrop Grumman
PO# TA2086004
Our Order# 0509051
QTY 40 EA
Q.C. asst. P. Smith
Authorized Signature

KAISER ALUMINUM
Trentwood Works - Spokane, WA 99215
Phone: (800) 367-2586

CERTIFIED TEST REPORT

Serial Number
4244600

CUSTOMER PO NUMBER:	WORK PACKAGE:	CUSTOMER PART NUMBER:	SHIP RUN/LOAD:	GOV'T CONTRACT NUMBER:
029386			102176/5	

KAISER ORDER NO:	LINE ITEM:	SHIP DATE:	ALLOY:	CLAD:	TEMPER:	PRODUCT DESCRIPTION:
1121561	3	9-NOV-2011	2024	BARE	T351	Sawed Plate

WEIGHT SHIPPED:	QUANTITY:	B/L NUMBER:	GAUGE:	DIAMETER/WIDTH:	LENGTH:
8026 LB	18 PCS EST.	2034449	0.5000 IN	60.500 IN	144.500 IN

MHU 1539302: LOT 566454A5: 11 pieces;
MHU 1539304: LOT 566454A5: 7 pieces;

Certified Specifications

AMS 4037/RevN AMS-QQ-A-250/4/RevA ASTM B 209/Rev10

Test Code: 1504

Test Results

Lot: 566454A5 Cast 548 Drop 01 Ingot 3 Melted in USA

(ASTM E8/B557)
(EN 2002-1)

Tensile:	Temper	Dir / # Tests	Ultimate KSI (MPA)	Yield KSI (MPA)	Elongation %
	T351	LT / 2 (Min:Max)	67.4 : 67.5 (465 : 465)	44.4 : 44.8 (306 : 309)	20.0 : 20.1

(ASTM E1251)

Chemistry:	SI	FE	CU	MN	MG	CR	ZN	TI	V	ZR		OTHER
Actual	0.07	0.16	4.5	0.58	1.4	0.01	0.12	0.01	0.01	0.00	TOT	0.03

ALLOY LIMITS

2024	SI	FE	CU	MN	MG	CR	ZN	TI	V	ZR	OTHER	MAX
MIN	0.00	0.00	3.8	0.30	1.2	0.00	0.00	0.00	0.00	0.00	EACH	0.05
MAX	0.50	0.50	4.9	0.9	1.8	0.10	0.25	0.15	0.05	0.05	TOT	0.15

Aluminum Remainder

KAISER ALUMINUM
Trentwood Works - Spokane, WA 99215
Phone: (800) 367-2586

CERTIFIED TEST REPORT

Serial Number
4244600

CERTIFICATION

KAISER ALUMINUM FABRICATED PRODUCTS, LLC (KAISER) HEREBY CERTIFIES THAT METAL SHIPPED UNDER THIS ORDER WAS MELTED IN THE UNITED STATES OF AMERICA OR A QUALIFYING COUNTRY PER DFARS 225.872-1(a), WAS MANUFACTURED IN THE UNITED STATES OF AMERICA, AND MEETS THE REQUIREMENTS OF DFARS 252.225 FOR DOMESTIC CONTENT. THIS MATERIAL HAS BEEN INSPECTED, TESTED, AND FOUND IN CONFORMANCE WITH THE REQUIREMENTS OF THE APPLICABLE SPECIFICATIONS AS INDICATED HEREIN. ALL METAL WHICH IS SOLUTION HEAT TREATED COMPLIES WITH AMS 2772. ANY WARRANTY IS LIMITED TO THAT SHOWN ON KAISER'S STANDARD GENERAL TERMS AND CONDITIONS OF SALE. TEST REPORTS SHALL NOT BE REPRODUCED EXCEPT IN FULL, WITHOUT THE WRITTEN APPROVAL OF KAISER ALUMINUM FABRICATED PRODUCTS, LLC LABORATORY. THE RECORDING OF FALSE, FICTITIOUS, OR FRAUDULENT STATEMENTS OR ENTIRES ON THE CERTIFICATE MAY BE PUNISHED AS A FELONY UNDER FEDERAL LAW. ISO-9001:2000 CERTIFIED.

MIKE KLOCKE, LABORATORIES SUPERVISOR

TECHNICAL SERVICES LABORATORY

Northrop Grumman Corporation
925 South Oyster Bay Road, M/S U03-26
Bethpage, New York 11714-3582

LABORATORY REQUEST NUMBER: 37304-12

DATE: 10/29/2012

DIRECTED TO: (√) ☐ CHEMISTRY LABORATORY ☒ METALLURGY LABORATORY ☐ ADV-DEV TECH-OPS ☐ NDT LABORATORY ☐ OPERATIONS

PART NAME/PART NUMBER : A-10 –IV 3.3.5 Crack Growth (Option 1) For Drawing GT270KB003

TYPE OF MATERIAL: 2024-T351 Aluminum Plate (.50 Thick)

PROGRAM	PURCHASE ORDER NO.	JOB NUMBER/IOS	QUANTITY	Lot NO.
A-10				418964A3

SPECIFICATIONS: AMS QQ-A-250/4

SELLER OR CUSTOMER:

TYPE OF TEST OR ANALYSIS REQUIRED
Mechanical Properties of an A-10 IATP Control Points Test Material

PURPOSE OF TEST/BACKGROUND

SAMPLE DESCRIPTION/CONDITION/REMARKS

REQUESTED BY	MAIL STA.-BLDG	FAX	PHONE	LAB APPROVAL
Ken Grube/ Bob Fidnarick	Plant 26		516.346.9232	*John Callori*

FINDING OR RESULTS
THE ABOVE MATERIAL IS : (√) ☒ **SATISFACTORY** ☐ UNSATISFACTORY ☐ INFORMATION ONLY

REMARKS:

Properties (Longitudinal)	Test Results				Requirements, min. (Longitudinal)
Specimen Number	1	2	3	AVG	
Tensile Strength, ksi	68.3	68.5	69.3	68.7	64.0
Yield Strength, ksi	57.2	57.4	57.5	57.4	42.0
% Elongation in x 2 inches	16.5	16.5	16.5	16.5	12.0

Al Sinowitz
SIGNATURE

Kevin Cook
APPROVED

(TECHNICAL SERVICES LABORATORY FAX 516-575-9909)
FORM 1512 REV. May 11

All Signatures on File
REFERENCE NO.

Lawrence Ripak Co., Inc.

Certification

Order No.: 287455 - 274440
Date: 11/27/2012
Entry Date: 11/20/2012
Page: 1 of 1

To: NGRUMNY
NORTHROP GRUMMAN
925 South Oyster Bay Rd
M/S U03-26
Bethpage NY 11714-3582

Purchase Order No.: 50712
Packing List No.:

We are pleased to provide you with the following Certification

Quantity	Part Number / Part Name / Part Description	Pounds
33	GT270KB003-11	
	MAT: 2024-T3511	

Process Steps

Step: 1 **Process: Sp** **Equipment #:**

Comment: Note: Certification is void if material removal exceeds 10% of nominal Almen A intensity.
Shot Peen per AMS2430 Rev S (s/s AMS-S-13165 Rev A) Machine #: 1 OD Shot: ASR230 Hardness: 45-52Rc
Coverage: 100% Intensity: .010-.014A2 Actual: .0120A2 Technique Card: GT270KB003-11 REV N/C 11-26-12

Step: 2 **Process: Cl** **Equipment #:**

Acid clean per AMS2430 Rev S (s/s AMS-S-13165 Rev A) to remove shot peen residue Nitric Acid clean to remove shot peen residue

We certify that the processes listed have been performed in accordance with the specifications shown. Records are being maintained and are available for review.

D Castellano
Deborah Castellano
Planning/Cert Supervisor
Lawrence Ripak Co., Inc.

WESTPRO LAB
WWW.WESTPROLAB.COM

WESTERN PROFESSIONAL, INC.
3460 BRADY CT. NE
SALEM, OR 97301
PHONE (503)585-6263
FAX (503)585-6577
www.westprolab.com

ULTRASONICS / PHASED ARRAY / EDM
RESEARCH & DEVELOPEMENT

CUSTOMER: NORTHRUP GRUMMAN IT
P.O. #: 7500109901
S/N: PLATES 1 THRU 33
SIZE: 16" X 4" X .410"
HEAT #: UNKNOWN
MATERIAL: 2024-T351 ALUMINUM
DWG#: GT270KB003
DATE: 12-3-12

A-10 TRAINING VS NON-TRAINING MISISON
SPECTRA TEST SPECIMEN

PLATE #	DEPTH	LENGTH	WIDTH	TYPE
1	.0200"	.0301"	.0044"	CORNER NOTCH
2	.0187"	.0310"	.0046"	CORNER NOTCH
3	.0207"	.0307"	.0046"	CORNER NOTCH
4	.0200"	.0306"	.0047"	CORNER NOTCH
5	.0205"	.0309"	.0046"	CORNER NOTCH
6	.0194"	.0313"	.0045"	CORNER NOTCH
7	.0202"	.0310"	.0044"	CORNER NOTCH
8	.0203"	.0309"	.0048"	CORNER NOTCH
9	.0206"	.0306"	.0045"	CORNER NOTCH
10	.0211"	.0312"	.0044"	CORNER NOTCH
11	.0205"	.0298"	.0045"	CORNER NOTCH
12	.0204"	.0307"	.0046"	CORNER NOTCH
13	.0206"	.0313"	.0045"	CORNER NOTCH
14	.0204"	.0322"	.0048"	CORNER NOTCH
15	.0198"	.0324"	.0044"	CORNER NOTCH
16	.0208"	.0315"	.0046"	CORNER NOTCH
17	.0206"	.0323"	.0044"	CORNER NOTCH

PLATE #	DEPTH	LENGTH	WIDTH	TYPE
18	.0197"	.0323"	.0047"	CORNER NOTCH
19	.0204"	.0304"	.0046"	CORNER NOTCH
20	.0202"	.0298"	.0047"	CORNER NOTCH
21	.0211"	.0313"	.0045"	CORNER NOTCH
22	.0210"	.0317"	.0046"	CORNER NOTCH
23	.0199"	.0317"	.0048"	CORNER NOTCH
24	.0204"	.0316"	.0046"	CORNER NOTCH
25	.0198"	.0307"	.0045"	CORNER NOTCH
26	.0202"	.0314"	.0050"	CORNER NOTCH
27	.0205"	.0303"	.0044"	CORNER NOTCH
28	.0209"	.0312"	.0047"	CORNER NOTCH
29	.0202"	.0324"	.0045"	CORNER NOTCH
30	.0200"	.0317"	.0048"	CORNER NOTCH
31	.0201"	.0306"	.0047"	CORNER NOTCH
32	.0208"	.0319"	.0044"	CORNER NOTCH
33	.0206"	.0309"	.0048"	CORNER NOTCH

* SEE ATTACHED NOTE

NOTE: SEE ATTACHED CUSTOMER DRAWING FOR NOTCH REQUIREMENTS AND LOCATION.

FABRICATED BY: S. CHAMBERLAIN

ALL DIMENSIONS ARE MEASURED WITH DIMENSIONAL EQUIPMENT WHICH IS CERTIFIED AND TRACEABLE TO **NIST (#708) #5084918** AND **NIST (#783183) #5830553**. NUCLEAR REGULATORY COMMISSION RULES AND REGULATIONS 10 CFR PART 21 APPLIES TO THIS ORDER. ALL NOTCHES MANUFACTURED PER WESTPRO PROCEDURE WQC-IV.

APPROVED BY: Mitchell A. Dale

NORTHRUP GRUMMAN IT PO#7500109901 ALUMINUM SPECTRA SPECIMENS 1-33

FROM
WESTPRO
3460 BRADY COURT, N.E.
SALEM, OR 97303
PH. (503) 585-6263 • FAX (503) 585-6577

QUICK MEMO

DATE: 12-4-12

ATTENTION: Robert Fidnarick

TO

NORTHRUP GRUMMAN IT

SUBJECT PO# 7500109901
Plate specimen #10
2024 T351 Aluminum

MESSAGE

Please note:

Notch in the ~~.125~~ .156 (R7) " Ø hole is off center of the

12 0 Clock location but notch dimensions are

within the tolerance of Dwg# GT270KB003

NOTE (1) COUPON ID EDM NOTCH IS .025 INCHES BELOW THE .156 INCH DIAMETER HOLE CENTERLINE.

DISPOSITION: HOLD COUPON FOR FINAL SPARE OR USE AS TEST SETUP FOR SPECTRUM PROVE OUT

R7

SIGNED [signature] EDM DEPT.

A-10 -IV3.35 Crack growth Option 1 12/7/2012

Material: 2024T351 (.500 plate)
Heat number: 418964A3
Drawing No: GT270KB003-11
Coupon ID 1-33

A-10 TRAINING vs NON TRAINING MISSION COUPON MEASUREMENTS

Coupon ID	Thickness in	Width in	Hole dia in
1	0.410	4.000	0.156
2	0.409	4.000	0.156
3	0.410	4.001	0.156
4	0.410	4.001	0.156
5	0.410	4.001	0.156
6	0.410	4.000	0.156
7	0.410	4.001	0.156
8	0.410	4.001	0.156
9	0.410	3.999	0.156
10 (1)	0.410	4.000	0.156
11	0.410	4.000	0.156
12	0.410	4.000	0.156
13	0.412	4.000	0.156
14	0.409	3.999	0.156
15	0.410	4.000	0.156
16	0.410	3.999	0.156
17	0.409	4.000	0.156

Coupon ID	Thickness in	Width in	Hole dia in
18	0.410	4.000	0.156
19	0.411	4.000	0.156
20	0.410	3.999	0.157
21	0.411	4.000	0.156
22	0.410	4.000	0.155
23	0.411	4.000	0.156
24	0.411	4.000	0.156
25	0.409	4.000	0.156
26	0.410	4.000	0.156
27	0.410	4.000	0.156
28	0.409	4.000	0.156
29	0.410	3.990	0.156
30	0.410	4.000	0.156
31	0.410	4.000	0.156
32	0.409	4.000	0.156
33	0.410	4.000	0.156

Note: (1) Coupon 10 EDM notch was inadvertently machined .025 inches below the centerline.

APPENDIX B

FATIGUE MACHINE AND LOAD CELL CALIBRATION CERTIFICATIONS

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : 26-Oct-2010 CERTIFICATE NUMBER : 91102610134148

NVLAP

Lab code: 200301-0

Page 1 of 3

INSTRON

Instron
825 University Avenue
Norwood, MA 02062-2643
Telephone: (800) 473 - 7838
Fax: (781) 575 - 5755
Email: service_requests@instron.com

APPROVED SIGNATORY

John L Paul

Digitally signed by John Paul
DN: cn=John Paul, o=GeoTrust True Credentials Customer - [illegible], ou=CPS terms incorporated by reference liability limited., See True Credentials Express CPS www.geotrust.com/resources/CPS., Email control validated by GeoTrust., Identity authenticated by Registration Authority (RA)., Registration Authority (RA) - [illegible] com, email=John_Paul@instron.com [illegible] document

Type of Calibration: speed
Relevant Standard: speed
Date of Calibration: 26-Oct-2010

Customer Requested Due Date: 26-Oct-2011

Customer	U S Air Force Hill AFB 00 ACL/MADLM 7278 4TH ST Layton, UT 84056	**Machine**	
		Serial No :	CJ3037
		Make :	Instron
		Model :	8800R
P.O. Number :		Ambient Temperature :	73.9 °F
Contact :	Cody Hone		

Readout Verified

1. Digital Readout (in/min)

Resolution of Indicator: .0001 in/min

Certification Statement

This certifies that the speeds verified with machine indicator 1 (listed above) were verified by Instron in accordance with Instron work instruction ICA-8-07.

The acceptable field calibration tolerance for certification is ± 0.5% of reading for Instron machines. For other machines, check the manufacturers specifications.

Method of Verification

The testing machine was verified on-site at customer location. The testing machine was verified in the 'as found' condition with no adjustments carried out, unless otherwise noted in the comments section of this certificate.

The verification and equipment used conform to a controlled Quality Assurance program which meets the specifications outlined in ANSI/NCSL Z540-1, ISO 10012, ISO 9001:2000, and ISO/IEC 17025:2005. The Instron measurement equipment used for verification is traceable to NIST.

The results indicated on this certificate and report relate only to the items verified. If there are methods or data included that are not covered by the NVLAP accreditation it will be identified in the comments. Any limitations of use as a result of this verification will be indicated in the comments. This report must not be used to claim product endorsement by NVLAP or the United States government. This report shall not be reproduced, except in full, without the approval of Instron.

CalproSDS version 3.3

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : **26-Oct-2010** CERTIFICATE NUMBER : **91102610134148**

Datapoint Summary - Indicator 1 - Digital Readout(in/min)

Indicated Speed (in/min)	Run1 Error(%)	Run2 Error(%)	Run3 Error(%)	Repeat Error (%)	Uncertainty (in/min)*	Coverage Factor = k
1	.525	.546	.731	.206	.00209	2
.25	.340	.682	.869	.529	.00088	2.45
.1	.784	.850	.839	.066	.00017	2

**The reported expanded uncertainty of measurement is based on a combined uncertainty multipied by a coverage factor k to provide a level of confidence of approximately 95 %.*

Data - Indicator 1 - Digital Readout(in/min)

Temperature at start of verification : 73.9 °F

Indicated Speed (in/min)	Run 1 Disp. (in)	Run 1 Time (min)	Run 1 Actual Speed (in/min)	Run 2 Disp. (in)	Run 2 Time (min)	Run 2 Actual Speed (in/min)	Run 3 Disp. (in)	Run 3 Time (min)	Run 3 Actual Speed (in/min)
1	.3302	.33193	.994778	.3295	.33130	.994567	.3284	.33080	.992745
.25	.3223	1.29358	.249153	.3226	1.29920	.248307	.3171	1.27942	.247847
.1	.3645	3.67357	.099222	.3290	3.31797	.099157	.3816	3.84802	.099168

Temperature at end of verification : 74.1 °F

Direction of Displacement: Down

Verification Equipment

Make/Model	Serial No.	Description	Cal Agency	Uncertainty of Calibration	Resolution	Cal Date	Due Date
Boeckeler DDI	1041	Linear Gage	A.A.Jansson	.000139 in	.0001 in	8-May-08	8-Nov-10
EXTECH 445580	960503	Thermometer	SYPRIS	.5 °F	.1°F	19-Sep-10	19-Sep-12
---	5G658B1	Computer Clock	Instron Calibrati	10 ms	1 ms	19-Jul-10	19-Jul-12

The standards used for this verification are traceable to NIST.

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : **26-Oct-2010** CERTIFICATE NUMBER : **91102610134148**

Datapoint Summary - Indicator 1 - Digital Readout(in/min)

Indicated Speed (in/min)	Run1 Error(%)	Run2 Error(%)	Run3 Error(%)	Repeat Error (%)	Uncertainty (in/min)*	Coverage Factor = k
1	.525	.546	.731	.206	.00209	2
.25	.340	.682	.869	.529	.00088	2.45
.1	.784	.850	.839	.066	.00017	2

**The reported expanded uncertainty of measurement is based on a combined uncertainty multipied by a coverage factor k to provide a level of confidence of approximately 95 %.*

Data - Indicator 1 - Digital Readout(in/min)

Temperature at start of verification : 73.9 °F

Indicated Speed (in/min)	Run 1			Run 2			Run 3		
	Disp. (in)	Time (min)	Actual Speed (in/min)	Disp. (in)	Time (min)	Actual Speed (in/min)	Disp. (in)	Time (min)	Actual Speed (in/min)
1	.3302	.33193	.994778	.3295	.33130	.994567	.3284	.33080	.992745
.25	.3223	1.29358	.249153	.3226	1.29920	.248307	.3171	1.27942	.247847
.1	.3645	3.67357	.099222	.3290	3.31797	.099157	.3816	3.84802	.099168

Temperature at end of verification : 74.1 °F

Direction of Displacement: Down

Verification Equipment

Make/Model	Serial No.	Description	Cal Agency	Uncertainty of Calibration	Resolution	Cal Date	Due Date
Boeckeler DDI	1041	Linear Gage	A.A.Jansson	.000139 in	.0001 in	8-May-08	8-Nov-10
EXTECH 445580	960503	Thermometer	SYPRIS	.5 °F	.1°F	19-Sep-10	19-Sep-12
---	5G658B1	Computer Clock	Instron Calibrati	10 ms	1 ms	19-Jul-10	19-Jul-12

The standards used for this verification are traceable to NIST.

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : **26-Oct-2010** CERTIFICATE NUMBER : **91102610134148**

Comments

Verified By: John Paul
Service Engineer

CERTIFICATE OF CALIBRATION

ISSUED BY: INSTRON CALIBRATION LABORATORY

DATE OF ISSUE: 27-Oct-10   CERTIFICATE NUMBER: **91102710100102**

NVLAP

Lab code: 200301-0

Instron
825 University Avenue
Norwood, MA 02062-2643
Telephone: (800) 473-7838
Fax: (781) 575-5750
Email: service_requests@instron.com

APPROVED SIGNATORY

John L Paul

Digitally signed by John Paul
DN: cn=John Paul, o=GeoTrust True Credentials Customer - Organization not validated., ou=CPS terms incorporated by reference liability limited., See True Credentials Express CPS www.geotrust.com/resources/CPS., Email control validated by GeoTrust., Identity authenticated by Registration Authority (RA)., Registration Authority (RA) - Calibration_lab@instron.com, email=John_Paul@instron.com
Reason: I attest to the accuracy and integrity of this document

Type of Calibration: **Strain**
Relevant Standard: **ASTM E83 - 10**
Date of Calibration: **27-Oct-10**   **Customer Requested Due Date: 27-Oct-11**

Customer

Name:	U S Air Force Hill Air Force Base
Address:	00 ACL/MADLM 7278 4th St Layton UT 84056 WELDON.BETTS@HILL.AF.MIL
P.O./Contract No.:	
Contact:	Weldon Betts

Machine

Manufacturer:	Instron
Serial Number:	8800RCJ3037
System ID:	8800RCJ3037
Range Type:	Single

Transducer

Manufacturer:	Interlaken
Transducer ID:	3541-01/889078
Extensometer Type:	Type 2
Travel (Tension):	0.1 in
Gauge Length:	0.2 in
Mode:	Static (Tension)

Classification

The following indicators of the extensometer system were verified and classed:

Indicator Type	Description	Indicator Units	Range Full Scale (%)	System Class
1. GPIB		in	100	B-1

Certification Statement

All indicators listed above were verified on-site at customer location by Instron in accordance with ASTM E83.

The verification and equipment used conform to a controlled Quality Assurance program which meets the specifications outlined in ANSI/NCSL Z540-1, ISO 10012, ISO 9001:2000 and ISO/IEC 17025:2005.

The testing machine was verified in the 'as found' condition.

Instron Calpro Version 3.13

The results indicated on this certificate and the following report relate only to the items verified. If there are methods or data included that are not covered by the NVLAP accreditation it will be identified in the comments. Any limitations of use as a result of this verification will be indicated in the comments. This report must not be used to claim product endorsement by NVLAP or the United States government. This report shall not be reproduced, except in full, without the approval of the issuing laboratory.

CERTIFICATE OF CALIBRATION

NVLAP ACCREDITED CALIBRATION LABORATORY No. 200301-0

CERTIFICATE NUMBER:
91102710100102

Summary of Results

Indicator 1. - GPIB (in)

Range Full Scale (%)	Tested Range (in)	Mode	System Class*	Resolution (in)	Resolution Class	ASTM E83 Lower Limit (in)
100	0.01 to 0.1	Tension	B-1	0.0000005	A	0.00005

** System Class for a range is the worst of the following classes: resolution class, individual point error class, repeatability class and is also based on the measurement capability of the laboratory.*

Data Summary and Classification

Indicator 1. - GPIB (in)

% of Range	Run 1 Error Fixed (in)	Run 1 Error Relative (% of strain)	Run 2 Error Fixed (in)	Run 2 Error Relative (% of strain)	Repeat Error (in)	Worst Class	Uncertainty of Measurement* (in)
100% Range (Full Scale: 0.1 in)							
10	0.00005	0.481	0.00005	0.493	0.00000	B-1	0.000102
20	0.00001	0.043	0.00003	0.135	0.00002	B-1	0.000102
40	0.00015	0.369	0.00017	0.418	0.00002	B-1	0.000102
70	0.00010	0.138	0.00015	0.211	0.00005	B-1	0.000102
100	-0.00002	-0.019	0.00002	0.022	0.00004	A	0.000102

** The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95%.*

Data

Indicator 1. - GPIB (in)

% of Range	Run 1 Indicated (in)	Run 1 Applied (in)	Run 2 Indicated (in)	Run 2 Applied (in)
100% Range (Full Scale: 0.1 in)				
	Run Temperature: 73.0 °F		Run Temperature: 73.0 °F	
0	-0.0000012	0.000000	0.0000167	0.000000
10	0.0100469	0.010000	0.0100660	0.010000
20	0.0200073	0.020000	0.0200436	0.020000
40	0.0401462	0.040000	0.0401837	0.040000
70	0.0700951	0.070000	0.0701644	0.070000
100	0.0999797	0.100000	0.1000390	0.100000

Verification Equipment and Usage

Verification Equipment:

Make/Model	Serial Number	Description	Calibration Agency	Measurement Range	Cal Date	Cal Due
Extech 445580	960503	temp. indicator	Sypris	NA	19-Aug-10	19-Aug-12

Instron Calpro Version 3.13

CERTIFICATE OF CALIBRATION

NVLAP ACCREDITED CALIBRATION LABORATORY No. 200301-0

CERTIFICATE NUMBER:
91102710100102

Verification Equipment:

Make/Model	Serial Number	Description	Calibration Agency	Measurement Range	Cal Date	Cal Due
Boeckeler Micrometer 1338	32746	disp. indicator	A.A. Jansson	1.00 in	30-Oct-09	30-Oct-10

Verification Equipment Usage:

Measurement Type	Serial Number	Range (% Full Scale)	Percent(s) of Range
Displacement	32746	100	0/10/20/40/70/100

Instron standards are traceable to NIST and/or other National standards.

Comments

Verified by: John Paul
Field Service Engineer

NOTE: Clause 9 of ASTM E-83: 2006 states; It is recommended that extensometer systems be verified annually or more frequently if required. In no case shall the time interval between verifications exceed 18 months (unless an extensometer is being used in a long-time test running beyond the 18 month period). An extensometer system shall not be used after an adjustment or repair that could affect its accuracy without first verifying its accuracy utilizing the procedure described in this practice.

CERTIFICATE OF CALIBRATION

NVLAP

Lab code: 200301-0

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : 26-Oct-2010 CERTIFICATE NUMBER: 91102610125508

INSTRON

Instron
825 University Avenue
Norwood, MA 02062-2643
Telephone: (800) 473 - 7838
Fax: (781) 575 - 5755
Email: service_requests@instron.com

APPROVED SIGNATORY

John L Paul

Digitally signed by John Paul
DN: cn=John Paul, o=GeoTrust True Credentials Customer - Organization not validated., ou=CPS terms incorporated by reference liability limited., See True Credentials Express CPS www.geotrust.com/resources/CPS., Email control validated by GeoTrust., Identity authenticated by Registration Authority (RA)., Registration Authority (RA) - Calibration_lab@instron.com, email=John_Paul@instron.com
Reason: I attest to the accuracy and integrity of this document

Type of Calibration: linear
Relevant Standard: linear
Date of Calibration: 26-Oct-2010

Customer Requested Due Date: 26-Oct-2011

Customer	U S Air Force Hill AFB 00 ACL/MADLM 7278 4TH ST Layton, UT 84056
P.O. Number :	
Contact :	Cody Hone

Machine	
Serial No :	CJ3037
Make :	Instron
Model :	8800R
Ambient Temperature :	74.1 °F

Readout Verified

1. Digital Readout (in)

Certification Statement

This certifies that the displacements verified with machine indicator 1 (listed above) were verified by Instron in accordance with Instron work instruction ICA-8-07.

The acceptable field calibration tolerance for certification is ± 1.0% full travel for Instron machines. For other machines, check the manufacturers specifications.

Method of Verification

The testing machine was verified on-site at customer location. The testing machine was verified in the 'as found' condition with no adjustments carried out, unless otherwise noted in the comments section of this certificate.

The verification and equipment used conform to a controlled Quality Assurance program which meets the specifications outlined in ANSI/NCSL Z540-1, ISO 10012, ISO 9001:2000, and ISO/IEC 17025:2005. The Instron measurement equipment used for verification is traceable to NIST.

The results indicated on this certificate and report relate only to the items verified. If there are methods or data included that are not covered by the NVLAP accreditation it will be identified in the comments. Any limitations of use as a result of this verification will be indicated in the comments. This report must not be used to claim product endorsement by NVLAP or the United States government. This report shall not be reproduced, except in full, without the approval of Instron.

CalproSDS version 3.3

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : 26-Oct-2010 CERTIFICATE NUMBER: 91102610125508

Summary of Results

Tested Displacement Ranges(in)	Max Error (% FS)	Direction	Max Repeat Error (% FS)	Max Uncertainty(in)	Resolution (in)
0.60 - 3.00	0.46	Tension	0.008	0.0010	.0001
0.60 - 3.00	-1.00	Compression	0.030	0.0028	.0001

Datapoint Summary - Indicator 1 - Digital Readout(in)

Tension

Sugg Value	Run1 Error (% FS)	Run2 Error (% FS)	Run3 Error (% FS)	Repeat Error (% FS)	Uncertainty (in)*	Coverage Factor = k
0.6	-.037	-.037	-.038	.001	.0007	2.26
1.2	.130	.133	.138	.008	.0009	2.26
1.8	.342	.347	.347	.005	.0008	2.26
2.4	.455	.463	.462	.008	.0010	2.26
3	.427	.425	.430	.005	.0009	2.26

Compression

Sugg Value	Run1 Error (% FS)	Run2 Error (% FS)	Run3 Error (% FS)	Repeat Error (% FS)	Uncertainty (in)*	Coverage Factor = k
0.6	-.373	-.343	-.345	.030	.0028	3.18
1.2	-.750	-.762	-.762	.012	.0011	2.36
1.8	-.977	-.985	-.997	.020	.0017	2.78
2.4	-.945	-.945	-.950	.005	.0009	2.26
3	-.743	-.748	-.747	.005	.0009	2.26

**The reported expanded uncertainty of measurement is based on a combined uncertainty multipied by a coverage factor k to provide a level of confidence of approximately 95 %.*

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : **26-Oct-2010** CERTIFICATE NUMBER: **91102610125508**

Data - Indicator 1 - Digital Readout(in)

Temperature at start of verification : 74.1 °F

Tension

Sugg Value	Run 1 Applied	Run 1 Indicated	Run 2 Applied	Run 2 Indicated	Run 3 Applied	Run 3 Indicated
0.6	.6022	.6	.6022	.6	.6023	.6
1.2	1.1922	1.2	1.1920	1.2	1.1917	1.2
1.8	1.7795	1.8	1.7792	1.8	1.7792	1.8
2.4	2.3727	2.4	2.3722	2.4	2.3723	2.4
3	2.9744	3	2.9745	3	2.9742	3

Compression

Sugg Value	Run 1 Applied	Run 1 Indicated	Run 2 Applied	Run 2 Indicated	Run 3 Applied	Run 3 Indicated
0.6	.6224	.6	.6206	.6	.6207	.6
1.2	1.2450	1.2	1.2457	1.2	1.2457	1.2
1.8	1.8586	1.8	1.8591	1.8	1.8598	1.8
2.4	2.4567	2.4	2.4567	2.4	2.4570	2.4
3	3.0446	3	3.0449	3	3.0448	3

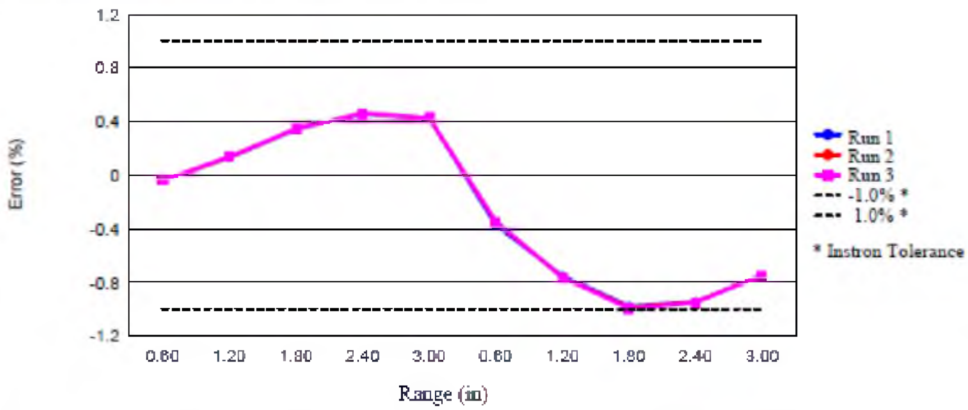
Temperature at end of verification : 73.9 °F

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : 26-Oct-2010 CERTIFICATE NUMBER: 91102610125508

Graphical Data - Indicator 1 -Digital Readout (in)



Verification Equipment

Make/Model	Serial No.	Description	Cal Agency	Uncertainty of Calibration	Resolution	Cal Date	Due Date
Boeckeler DDI	1041	Linear Gage	A.A.Jansson	.000139 in	.0001 in	8-May-08	8-Nov-10
EXTECH 445580	960503	Thermometer	SYPRIS	.5 °F	.1 °F	19-Sep-10	19-Sep-12

The standards used for this verification are traceable to NIST.

Comments

Verified By: John Paul

Service Engineer

CalproSDS version 3.3

APPENDIX C

NEWMAN RAJU STRESS INTENSITY EQUATION

MAIN EQUATIONS FOR CALCULATING THE STRESS INTENSITY IN A SINGLE CORNER CRACK OF A HOLE

$$K_{one\ crack} = \sqrt{\left(\frac{4}{\pi} + \frac{ac}{2tr}\right) \Big/ \left(\frac{4}{\pi} + \frac{ac}{tr}\right)}\, K_{two\ cracks}$$

$$K_{two\ cracks} = (St + H_{ch}S_b)\sqrt{\pi\frac{a}{Q}}F_{ch}\left(\frac{a}{c}, \frac{a}{t}, \frac{r}{t}, \frac{r}{b}, \frac{c}{b}, \frac{c}{b}, \phi\right)$$

for $0.2 < {}^{a}/_{c} < 2, {}^{a}/_{t} < 1, 0.5 < {}^{r}/_{t} < 2, {}^{(r+c)}/_{b} < 0.5$, and $0 < \phi < {}^{\pi}/_{2}$

$$F_{ch} = \left[M_1 + M_2\left(\frac{a}{t}\right)^2 + M_3\left(\frac{a}{t}\right)^4\right] g_1 g_2 g_3 g_4 f_\phi f_w$$

for ${}^{a}/_{c} < 1$: $M_1 = 1.13 - 0.09({}^{a}/_{c}),\ M_2 = -0.54 + 0.89/(0.2 + {}^{a}/_{c}),$

$$M_3 = 0.5 - 1/(0.65 + {}^{a}/_{c}) + 14(1 - {}^{a}/_{c})^{24},$$

$$g_1 = 1 + \left[0.1 + 0.35({}^{a}/_{t})^2\right](1 - \sin\phi)^2,$$

$$g_2 = \frac{1 + 0.358\lambda + 1.425\lambda^2 - 1.578\lambda^3 + 2.156\lambda^4}{1 + 0.13\lambda^2},$$

where $\lambda = 1/(1 + {}^{c}/_{r}\cos(\mu\phi))$.

$$g_3 = (1 + 0.04\,{}^{a}/_{c})[1 + 0.1(1 - \cos\phi)^2]\left[0.85 + .15({}^{a}/_{c})^{1/4}\right],$$

$$g_4 = 1 - 0.7\left(1 - {}^{a}/_{t}\right)({}^{a}/_{c} - 0.2)(1 - {}^{a}/_{c}),\ f_\phi = [({}^{a}/_{c})^2(\cos\phi)^2 + (\sin\phi)^2]^{1/4}$$

$$f_w = \left\{\sec\left(\frac{\pi r}{2b}\right)\sec\left[\frac{\pi(2r + nc)}{4(b - c) + 2nc}\sqrt{\frac{a}{t}}\right]\right\}^{1/2}$$

APPENDIX D

PROCEDURES FOR AFGROW ANALYSIS

STEP BY STEP PROCESS TO USE AFGROW BASED ON THE GUIDELINES PREPARED BY THE UNITED STATES AIR FORCE

1. Create Title: Brief description of model.
2. Select Material: This analysis used a file containing material properties and parameters for the Forman equation to simulate the 2024-T351 Aluminum Alloy in the AFGROW program. The information in the file is a general guide and some material properties may need to be adjusted based on manufacturing thicknesses or other factors. Reference the Metallic Materials Properties Development and Standardization (MMPDS) to verify correct material properties.
3. Create Model: From a selection of “Classic Models”, choose the appropriate geometric model. For this analysis, the “Single Corner Crack at Hole” model was chosen.
a. Enter problem geometric factors including: thickness, width, hole diameter, initial flaw size (IFS), offset, etc.
i. Check: keep A/C constant
ii. Uncheck: Oblique through crack
iii. IFS: Unless otherwise specified, the initial flaw size should be the same in both the “A” and “C” directions. For this analysis an average of the precrack sizes, for each type of test conducted, were used.
b. Select Load Type: Ratio of tension or bearing stress to reference stress must be input for each load case (tension stress fraction = 1.0 if bearing stress is zero). The test for this analysis was purely tensile.
4. Open Spectrum File: For this analysis the A and B spectrum files, specifically created to be used in AFGROW, were utilized. AFGROW require that the files be normalized with the greatest value given a value of 1.0 and all other loads be represented as a fraction of the highest load.
a. Stress Multiplication Factor (SMF): Enter the max stress of the spectrum. Since the values in the spectrum files are representative of loads the SMF had to include a conversion factor to make the values in the spectrum files convert to stresses.
5. Select a Retardation Model: For this analysis several retardation models were attempted to obtain the best fit to the test data.
6. Predict Function Preferences: Used for establishing various analysis criteria and outputs.
a. Select Growth Increments: Cycle by Cycle Beta and Spectrum calculation. Use a Max Growth Increment of 0.25%
b. Enter Output Intervals: Specify crack growth increments. Increment = 0.01”
c. Enter Number of Hours per Pass: Conversion factor for calculating effective flight hours (EFH) from segment count.
d. Select Output Options: Typically the user will select the data file and plot file options for crack growth data.
e. Select Propagation Limits: Unless otherwise specified use the Kmax and the Net Section Section Yield failure criteria.
f. If using Forman, as was done for this analysis, select User-Defined Kmax and enter an appropriate value for the material.
g. Enter Transition to Through Crack: Use default unless otherwise specified.

7. Select Stress State: Use default unless otherwise specified.
8. Select Beta Criteria: Use AFGROW standard solution betas for standard geometries.
9. At this point the user is ready to run the analysis.

APPENDIX E

CRACK GROWTH DATA SHEETS

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-1
Width: 4.00 in Thick: .410 in Area: 1.64 in^2

Precrack Information

Precrack Date: May 31, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0301 in Bore EDM Length: 0.0044 in

Testing Information

Test Date: March 3, 2014 Loading Condition: Variable Amplitude
Constant Load Rate: 100 kip/sec Spectrum: Baseline Spectrum A
Surface EDM Length: .042 in Hole Diameter: .250 in
Peak Stress: 27.9 ksi

EFH	Crack Length (inches)				
	EDM Side			Opposite Side	
	Front	Back	Bore	Front	Back
0	0.047		0.097		
3257.108	0.061		0.12		
4885.662	0.074		0.149		
6514.216	0.086		0.149		
8142.77	0.103		0.166		
9119.902	0.123		0.181		
9771.324	0.124		0.185		
10422.75	0.125		0.192		
11074.17	0.134		0.202		
11725.59	0.143		0.213		
12377.01	0.152		0.226		
13028.43	0.163		0.233		
13679.85	0.173		0.244		
14331.28	0.183		0.249		
14982.7	0.196		0.267		
15634.12	0.206		0.282		
16285.54	0.223		0.2915		
16936.96	0.234		0.301		

17588.38	0.249		0.314		
18239.8	0.267		0.339		
18565.52	0.271		0.35		
18891.23	0.282		0.357		
19216.94	0.288		0.363		
19542.65	0.294		0.3745		
19868.36	0.302		0.383		
20194.07	0.311	0.002			
20356.92	0.314	0.026			
20682.64	0.321	0.066			
21008.35	0.33	0.1085			
21334.06	0.348	0.152			
21496.91	0.349	0.1665			
21822.62	0.355	0.1955			
22148.33	0.359	0.223			
22474.04	0.372	0.2455			
22799.76	0.381	0.2645			
23125.47	0.395	0.284			
23451.18	0.406	0.299			
23776.89	0.415	0.318			
24102.6	0.429	0.3345			
24428.31	0.441	0.3565			
24754.02	0.457	0.373			
25079.73	0.472	0.392			
25405.44	0.609	0.537			
25731.15	0.623	0.5565		0.024	
26056.86	0.629	0.577		0.038	
26382.57	0.654	0.5965		0.047	
26708.29	0.667	0.616		0.056	
27034	0.688	0.645		0.074	0.04
27359.71	0.713	0.664		0.091	0.062
27685.42	0.733	0.693		0.104	0.083
28011.13	0.751	0.716		0.127	0.103
28336.84	0.78	0.743		0.148	0.124
28662.55	0.804	0.78		0.173	0.153
28988.26	0.837	0.814		0.206	0.2
29313.97	0.872	0.855		0.243	0.233
29476.83	0.888	0.879		0.259	0.25
29639.68	0.905	0.898		0.28	0.271

29802.54	0.927	0.917		0.299	0.295
29965.39	0.963	0.945		0.325	0.327
30128.25	0.979	0.9695		0.339	0.35
30291.1	1.015	1.008		0.372	0.383
30453.96	1.09	1.082		0.425	0.44
30551.67	1.111	1.117		0.465	0.4
Final Specimen Fracture					

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-2
Width: 4.00 in Thick: .409 in Area: 1.64 in^2

Precrack Information
Precrack Date: Jun 3, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter:0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0310 in Bore EDM Length: 0.0046 in

Testing Information
Test Date: N/A Loading Condition: N/A
Constant Load Rate:N/A Spectrum: N/A
Surface EDM Length: N/A Hole Diameter N/A
Peak Stress: N/A

This sample exceeded the precrack final size criteria and was removed from the test matrix and used as for load frame calibration.

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-3
Width: 4.00 in Thick: .409 in Area: 1.64 in^2

Precrack Information
Precrack Date: Jun 4, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter:0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0307 in Bore EDM Length: 0.0046 in

Testing Information
Test Date: Feb 24, 2014 Loading Condition: Variable Amplitude
Constant Load Rate:100 Kips/sec Spectrum: Spectrum A+B Combination
Surface EDM Length: 0.0465 in Hole Diameter .253 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.0465		0.0613			
2550	0.06642		0.1013			
4916	0.08368		0.1385			
7595	0.10264		0.1665			
10441	0.13682		0.2008			Switch to B
63456	0.14446		0.2065			
108481	0.1887		0.2228			
142068	0.21598		0.2526			
161545	0.24468		0.3140			

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-4

Width: 4.00 in Thick: .410 in Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 5, 2013 Loading Condition: Constant Amplitude R=.05

Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi

Surface EDM Length: 0.0306 in Bore EDM Length: 0.0047 in

Testing Information

Test Date: Aug 01, 2013 Loading Condition: Variable Amplitude

Constant Load Rate: 100 Kips/sec Spectrum: Baseline Spectrum A

Surface EDM Length: 0.04504 in Hole Diameter .255 in

Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)				
	EDM Side			Opposite Side	
	Front	Back	Bore	Front	Back
0	0.04504		0.0826		
113	0.04632		0.0847		
168	0.04856		0.0847		
274	0.04864		0.09314		
299	0.04864		0.095878		
334	0.05108		0.095878		
399	0.05286		0.098468		
532	0.05412		0.100614		
595	0.05412		0.102908		

709	0.05752		0.1082		
1639	0.06178		0.115638		
2349	0.06818		0.120041		
3340	0.07958		0.13451		
4056	0.08698		0.145389		
4450	0.09416		0.146869		
5073	0.10376		0.156527		
6112	0.11146		0.176176		
7403	0.12428		0.188425		
8257	0.14378		0.200932		
8589	0.14656		0.207963		
9115	0.16172		0.211927		
9739	0.17546		0.219915		
10566	0.19384		0.227945		
11474	0.2093		0.255217		
12174	0.2242		0.282193		
13218	0.25536		0.313905		
13704	0.27198		0.335997		
14364	0.29264		0.356164		
14922	0.30938		0.41056		
15308	0.32116			0.42842	0.13376
15482	0.33384			0.4411	0.16326
15667	0.33492			0.44218	0.2016
15856	0.34042			0.44768	0.22066
16301	0.36074			0.468	0.2714
16733	0.37378			0.48104	0.3094
17075	0.38422			0.49148	0.33738
17471	0.4083			0.51556	0.36192
17925	0.42572			0.53298	0.39708
18305	0.44692			0.55418	0.43438
18985	0.48256			0.58982	0.4724
19865	0.53636			0.64362	0.54432
20354	0.57386			0.68112	0.59376
20630	0.59994			0.7072	0.62574
21003	0.63684			0.7441	0.67202
21461	0.69024			0.7975	0.72912
21918	0.75092			0.85818	0.79342
22210	0.79748			0.90474	0.84936

22355	0.81952			0.92678	0.8745
22526	0.87478			0.98204	0.92992
22698	0.91818			1.02544	0.98136
22855	0.96624			1.0735	1.0192
22996	1.01956			1.12682	1.08222
23079	1.07238			1.17964	1.15046
23136	1.18318			1.29044	1.2613

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-5
Width: 4.00 in Thick: .410 in Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 5, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0309 in Bore EDM Length: 0.0046 in

Testing Information

Test Date: Feb 14, 2014 Loading Condition: Variable Amplitude
Constant Load Rate: 200 Kips/sec Spectrum: Baseline Spectrum A
Surface EDM Length: 0.0353 in Hole Diameter .254 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)				
	EDM Side			Opposite Side	
	Front	Back	Bore	Front	Back
0	0.03534		0.1016		
169	0.035		0.1016		
1833	0.0512		0.1251		
2811	0.06822		0.1433		
5107	0.07044		0.1433		
6451	0.0871		0.1433		
9086	0.11822		0.1855		
11995	0.14892		0.2291		
15182	0.198		0.2595		
18187	0.26122		0.3344		
20949	0.3326	0.14084			
22501	0.38306	0.26108			
25882	0.50552	0.4532			
27459	0.60744	0.56146			
28382	0.680006				
30519	0.92902				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-6
Width: 4.00 in Thick: .410 in Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 7, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0313 in Bore EDM Length: 0.0045 in

Testing Information

Test Date: Sept 3, 2013 Loading Condition: Variable Amplitude
Constant Load Rate: 150 Kips/sec Spectrum: Spectrum A+B Combo 1
Surface EDM Length: 0.055 in Hole Diameter .250 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.055		0.138819			
984	0.08608		0.152384			
2301	0.09748		0.177			
3010	0.10728		0.185932			
4027	0.11978		0.194461			
4409	0.12488		0.198522			Switch to B
36588	0.12488		0.1985			
45735	0.12488		0.1985			
57169	0.12488		0.1985			
73545	0.1596		0.211397			
83467	0.1596		0.211397			
90602	0.16788		0.224617			
97195	0.1751		0.231298			
104456	0.17956		0.241451			

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-7
Width: 4.00 in Thick: .410 in Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 7, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0310 in Bore EDM Length: 0.0044 in

Testing Information

Test Date: Feb 6, 2014 Loading Condition: Variable Amplitude
Constant Load Rate: 100 Kips/sec Spectrum: Spectrum A+B Combo 1
Surface EDM Length: 0.044 in Hole Diameter .251 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.044		0.094			
163	0.049		0.099			
326	0.050		0.108			
489	0.050		0.109			
651	0.053		0.118			

977	0.056		0.126			
1629	0.058		0.13			
2280	0.062		0.132			
3257	0.068		0.161			
3583	0.069		0.169			
3909	0.072		0.173			
4234	0.080		0.173			
4560	0.084		0.175			
4886	0.085		0.177			
5211	0.086		0.179			
5537	0.087		0.179			
5863	0.089		0.179			
6514	0.092		0.179			
6840	0.095		0.179			
7166	0.100		0.179			
8143	0.108		0.179			
8794	0.116		0.186			
9120	0.121		0.192			
9169	0.121		0.2			Switch to B
45735	0.126		0.251			
91471	0.148		0.273			
109765	0.164		0.289			
118912	0.173		0.298			
128059	0.186		0.311			
137206	0.196		0.321			
146353	0.208		0.333			
155500	0.220		0.345			
164647	0.233		0.358			
173794	0.243		0.368			
182941	0.253		0.378			
192088	0.267		0.392			

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-8
Width: 4.00 in Thick: .410 in Area: 1.64 in^2
Precrack Information
Precrack Date: Jun 7, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi

Surface EDM Length: 0.0309 in Bore EDM Length: 0.0048 in

Testing Information
Test Date: Feb 21, 2014 Loading Condition: Variable Amplitude
Constant Load Rate: 200 Kips/sec Spectrum: Spectrum A+B Combo 2
Surface EDM Length: 0.028 in Hole Diameter .253 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.0275		0.072			
3282	0.06074		0.111			
6180	0.07742		0.128			
9741	0.10948		0.193			
12951	0.1369		0.231			
15193	0.17308		0.271			
18223	0.21852		0.328			Switch to B
26913	0.21852		0.328			
66024	0.22854		0.373			
123931	0.29704		0.373			
164969	0.3622	0.269				
185701	0.41348	0.353				
211164	0.47238	0.408				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-9
Width: 4.00 in Thick: .410 in Area: 1.64 in^2

Precrack Information
Precrack Date: Jun 10, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0306 in Bore EDM Length: 0.0045 in

Testing Information
Test Date: Mar 20, 2014 Loading Condition: Variable Amplitude
Constant Load Rate: 100 Kips/sec Spectrum: Spectrum A+B Combo 3
Surface EDM Length: 0.0345 in Hole Diameter .252 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)			Comments
	EDM Side	Opposite Side		

	Front	Back	Bore	Front	Back	
0	0.035		0.077			
3257	0.058		0.112			
4886	0.066		0.124			
6514	0.077		0.137			
8143	0.087		0.148			
9771	0.100		0.173			
11400	0.115		0.183			
13028	0.133		0.204			
14657	0.153		0.223			
16286	0.176		0.253			
17914	0.200		0.278			
19543	0.233		0.320			
20194	0.245		0.338			
20845	0.260		0.343			
21497	0.275		0.352			
22148	0.290		0.365			Switch to B
22832	0.304	0.008				
32015	0.310	0.023				
54882	0.313	0.039				
68603	0.319	0.056				
75746	0.326	0.100				
80037	0.330	0.139				
84610	0.335	0.173				
89184	0.343	0.218				
93757	0.347	0.252				
98331	0.356	0.284				
102904	0.363	0.294				
107478	0.374	0.316				
112051	0.384	0.334				
116625	0.396	0.350				
121198	0.405	0.359				
128059	0.422	0.378				
132632	0.433	0.392				
137206	0.445	0.409				
141779	0.456	0.426				
146353	0.469	0.433				
150926	0.482	0.453				
160073	0.509	0.474		0.09		

164647	0.520	0.490		0.1		
173794	0.556	0.516		0.108		
178367	0.562	0.529		0.112		
182941	0.580	0.540		0.0823		
187514	0.593	0.561		0.128		
192088	0.609	0.582		0.134		
196661	0.626	0.595		0.144		
201235	0.642	0.614		0.155		
205808	0.658	0.635		0.17		
210382	0.675	0.652		0.181		
214955	0.697	0.674		0.194	0.124	
219529	0.723	0.692		0.217	0.143	
224102	0.743	0.718		0.234	0.162	
228676	0.767	0.746		0.255	0.192	
233249	0.795	0.780		0.279	0.218	
237823	0.823	0.810		0.305	0.243	
242397	0.856	0.841		0.336	0.277	
246970	0.894	0.876		0.36	0.303	
251544	0.933	0.918		0.402	0.341	
256117	0.973	0.953		0.436	0.407	
260691	1.027	1.017		0.479	0.459	
265264	1.110	1.106		0.533	0.523	
269838	1.380	1.302		0.631	0.665	
270039	**Final Specimen Fracture**					

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-10
Width: 4.00 in Thick: .410 in Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 10, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0312 in Bore EDM Length: 0.0044 in

Testing Information

Test Date: Feb 14, 2014 Loading Condition: Variable Amplitude
Constant Load Rate: 100 Kips/sec Spectrum: Spectrum A+B Combo 2
Surface EDM Length: 0.0300 in Hole Diameter .251 in
Peak Stress: 27.9 Ksi

Coupon 10 EDM Notch was inadvertently machined .025 inches below the centerline.

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.030		0.087			
326	0.036		0.091			
651	0.040		0.093			
1303	0.047		0.093			
1954	0.049		0.093			
2606	0.052		0.103			
3257	0.057		0.109			
3909	0.061		0.109			
4886	0.064		0.109			
5537	0.069		0.121			
6189	0.074		0.129			
6840	0.081		0.137			
7491	0.088		0.141			
8143	0.092		0.151			
8794	0.098		0.151			
9771	0.112		0.161			
10423	0.118		0.171			
11074	0.125		0.176			
11726	0.134		0.174			
12377	0.140		0.184			
13028	0.150		0.200			
13680	0.157		0.204			
14331	0.168		0.214			
14983	0.175		0.222			
15634	0.188		0.232			
16286	0.200		0.250			
16611	0.203		0.285			
16937	0.208		0.292			
17100	0.211		0.297			
17426	0.216		0.305			
17751	0.222		0.321			
17849	0.223		0.329			Switch to B

40717	0.228		0.331			
63584	0.23		0.335			
104746	0.257		0.345			
123040	0.274		0.351			
132187	0.292		0.363			
136760	0.2985		0.365			
141334	0.309		0.371			
145907	0.32		0.385			
150481	0.32		0.391			
155055	0.332	0.007				
157341	0.333	0.138				
159628	0.337	0.173				
161915	0.341	0.191				
164202	0.348	0.211				
168775	0.354	0.238				
173349	0.361	0.251				
177922	0.369	0.269				
182496	0.375	0.279				
187069	0.385	0.29				
191643	0.394	0.305				
196216	0.405	0.331				
200790	0.412	0.337				
205363	0.42	0.351				
209937	0.432	0.366				
214510	0.441	0.38				
219084	0.454	0.392				
223657	0.463	0.402				
228231	0.475	0.42				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-11
Width: 4.00 in Thick: .410 in Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 10, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0298 in Bore EDM Length: 0.0045 in

Testing Information

Test Date: Aug 21, 2013 Loading Condition: Variable Amplitude

Constant Load Rate: 300 Kips/sec Spectrum: Spectrum A+B Combo 2
Surface EDM Length: 0.0500 in Hole Diameter .251 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.050		0.094			
240	0.059		0.119			
493	0.068		0.132			
1066	0.082		0.149			
1710	0.093		0.157			
2355	0.101		0.173			
3046	0.118		0.185			
3548	0.129		0.196			
4445	0.148		0.209			
5153	0.161		0.237			
5830	0.176		0.255			
6387	0.194		0.271			
6822	0.207		0.271			
7365	0.222		0.296			
7801	0.238		0.319			
8097	0.246		0.328			Switch to B
35016	0.260		0.334			
50130	0.288		0.357			
58647	0.307		0.370			
66675	0.317		0.405			
67260	0.322		0.413			
73788	0.331	0.190				
77615	0.338	0.236				
89727	0.366	0.298				
98641	0.379	0.340				
113300	0.424	0.397				
126478	0.468	0.447				
141295	0.516	0.495				
160558	0.585	0.586				
172814	0.627	0.636				
178358	0.659	0.658				
190517	0.698	0.714				
197275	0.730	0.754				

201005	0.757	0.781				
206970	0.787	0.805				
218074	0.823	0.835				
233025	0.860	0.870				
255857	0.906	0.942				
284172	0.961	0.994				
316499	0.997	1.040				
352517	1.064	1.089				
391018	1.092	1.126				
433269	1.154	1.140				
478418	1.228	1.225				
525310	1.330	1.327				
572410	**Final Specimen Fracture**					

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-12
Width: 4.00 in Thick: .410 in Area: 1.64 in^2

Precrack Information

Precrack Date: May 331, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0307 in Bore EDM Length: 0.0046 in

Testing Information

Test Date: Aug 21, 2013 Loading Condition: Variable Amplitude
Constant Load Rate: 100 Kips/sec Spectrum: Spectrum A+B Combo 3
Surface EDM Length: 0.0467 in Hole Diameter .251 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.047		0.108			
578	0.063		0.121			
2544	0.085		0.151			
3977	0.101		0.168			
5898	0.121		0.197			
7790	0.158		0.233			
10069	0.202		0.296			
11781	0.239		0.304			
13327	0.271		0.348			
13792	0.292		0.355			
14221	0.304		0.381			
14322	0.304		0.400			
14387	0.304	0.005	0.410			Switch to B
23203	0.304	0.016				
27820	0.307	0.021				
44971	0.307	0.026				
61732	0.307	0.066				
90850	0.354	0.223				
117332	0.420	0.337				
130629	0.454	0.381				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-13
Width: 4.00 in Thick: .412 in Area: 1.65 in^2

Precrack Information

Precrack Date: Jun 12, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0307 in Bore EDM Length: 0.0046 in

Testing Information

Test Date: Sept 4, 2013 Loading Condition: Variable Amplitude
Constant Load Rate: 140 Kips/sec Spectrum: Spectrum A+B Combo 3
Surface EDM Length: 0.0458 in Hole Diameter .250 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.046		0.106			
1372	0.063		0.115			
2703	0.072		0.126			
4353	0.090		0.137			
6423	0.107		0.155			
9295	0.140		0.174			
11282	0.166		0.224			
14127	0.214		0.288			
15885	0.254		0.320			
17137	0.284		0.356			
18365	0.308		0.387			Switch to B
19521	0.335	0.080				
46905	0.343	0.110				
67041	0.353	0.154				
76910	0.356	0.190				
86981	0.371	0.233				
98141	0.404	0.281				
107895	0.421	0.317				
116967	0.450	0.343				
126350	0.470	0.384				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-27
Width: 4.00 in Thick: .412 in Area: 1.65 in^2

Precrack Information
Precrack Date: Jun 15, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 5 hz Hole Diameter:0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0303 in Bore EDM Length: 0.0044 in

Testing Information
Test Date: Sept 4, 2013 Loading Condition: Variable Amplitude
Constant Load Rate:140 Kips/sec Spectrum: Baseline B Spectrum
Surface EDM Length: 0.0420 in Hole Diameter .250 in
Peak Stress: 23.04 Ksi

EFH	Crack Length (inches)			
	EDM Side		Opposite Side	
	Front	Back	Front	Back
0	0.042			
91470.39	0.085			
137205.6	0.117			
182940.8	0.1505			
228676	0.1975			
274411.2	0.2555			
304139	0.298	0.004		
324719.9	0.327	0.182		
333866.9	0.3425	0.218		
365881.5	0.403	0.32		
402469.7	0.481	0.4255		
425337.3	0.551	0.499		
443631.4	0.603	0.557		
461925.5	0.6625	0.626		
480219.5	0.7365	0.7075		
498513.6	0.83	0.814	0.124	0.153
508118	0.8905	0.8705	0.18	0.2105
516807.7	0.9745	0.9495	0.2415	0.2775
521381.2	1.014	1.004	0.282	0.321
530528.2	1.158	1.148	0.414	0.441
534973.7	Final Specimen Fracture			

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-28
Width: 4.00 in Thick: .409 in Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 16, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 5 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0312 in Bore EDM Length: 0.0047 in

Testing Information

Test Date: Mar 2, 2014 Loading Condition: Variable Amplitude
Constant Load Rate: 140 Kips/sec Spectrum: Baseline B Spectrum
Surface EDM Length: 0.0414 in Hole Diameter .250 in
Peak Stress: 23.04 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			posite Side		
	Front	Back	Bore	Front	Back	
0	0.0414		0.0000			
185806	0.0633		0.0000			
360030	0.0824		0.0000			
583627	0.11858		0.0000			
772465	0.15376		0.0000			
977761	0.20184		0.0000			
1197855	0.26462		0.0000			
1378902	0.32788	0.14352				
1549388	0.39762	0.29048				
1688747	0.47056	0.38574				
1881776	0.58938	0.53562				
2092317	0.79418	0.7655				
2256435	1.13454	1.13488				
2270026	1.2475	1.205				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-29
Width: 4.00 in Thick: .409 in Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 17, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 5 hz Hole Diameter: 0.156 in Peak Stress: 16.1 ksi
Surface EDM Length: 0.0324 in Bore EDM Length: 0.0045 in

Testing Information

Test Date: Sept 11, 2013 Loading Condition: Variable Amplitude
Constant Load Rate: 140 Kips/sec Spectrum: Baseline B Spectrum
Surface EDM Length: 0.0433 in Hole Diameter .250 in
Peak Stress: 23.04 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.043		0.112			
26593	0.053		0.121			
56467	0.071		0.121			
89204	0.094		0.127			
112826	0.094		0.166			
128092	0.117		0.174			
173189	0.149		0.219			
212170	0.186		0.224			
242343	0.220		0.245			
272791	0.259		0.315			
290604	0.285		0.383			
325531	0.336	0.117				
374632	0.432	0.261				
395772	0.478	0.331				
422695	0.554	0.418				
443350	0.613	0.483				
458555	0.664	0.561				
474135	0.717	0.609				
481853	0.746	0.644				
504162	0.852	0.753				
521701	0.967	0.876				
534735	1.084	1.004				
539575	1.170	1.081				
541754	1.223	1.274				
543121	1.340	1.313				
543632	Final Specimen Fracture					

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-30
Width: 4.00 in Thick: .410 in Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 18, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 5 hz Hole Diameter: 0.156 in Peak Stress: 16.1 ksi
Surface EDM Length: 0.0317 in Bore EDM Length: 0.0048 in

Testing Information

Test Date: Mar 14, 2014 Loading Condition: Variable Amplitude
Constant Load Rate: 100 Kips/sec Spectrum: Baseline A Spectrum
Surface EDM Length: 0.0438 in Hole Diameter .250 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.044		0.075			
1045	0.044		0.087			
3238	0.059		0.096			
6719	0.077		0.107			
9192	0.112		0.164			
10800	0.129		0.182			
12675	0.146		0.213			
14457	0.168		0.221			
17279	0.217		0.239			
18210	0.238		0.306			
19330	0.268		0.322			
21009	0.304		0.342			
23270	0.356	0.113				
25782	0.420	0.293				
27679	0.496	0.401				
28924	0.562	0.489				
30065	0.639	0.581				
30825	0.698	0.660				
31262	0.753	0.703				
31875	0.822	0.788				
32534	0.953	0.926				
32738	1.026	0.994				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-31
Width: 4.00 in Thick: .410 in Area: 1.64 in^2

Precrack Information
Precrack Date: July 22, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 5 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0306 in Bore EDM Length: 0.0047 in

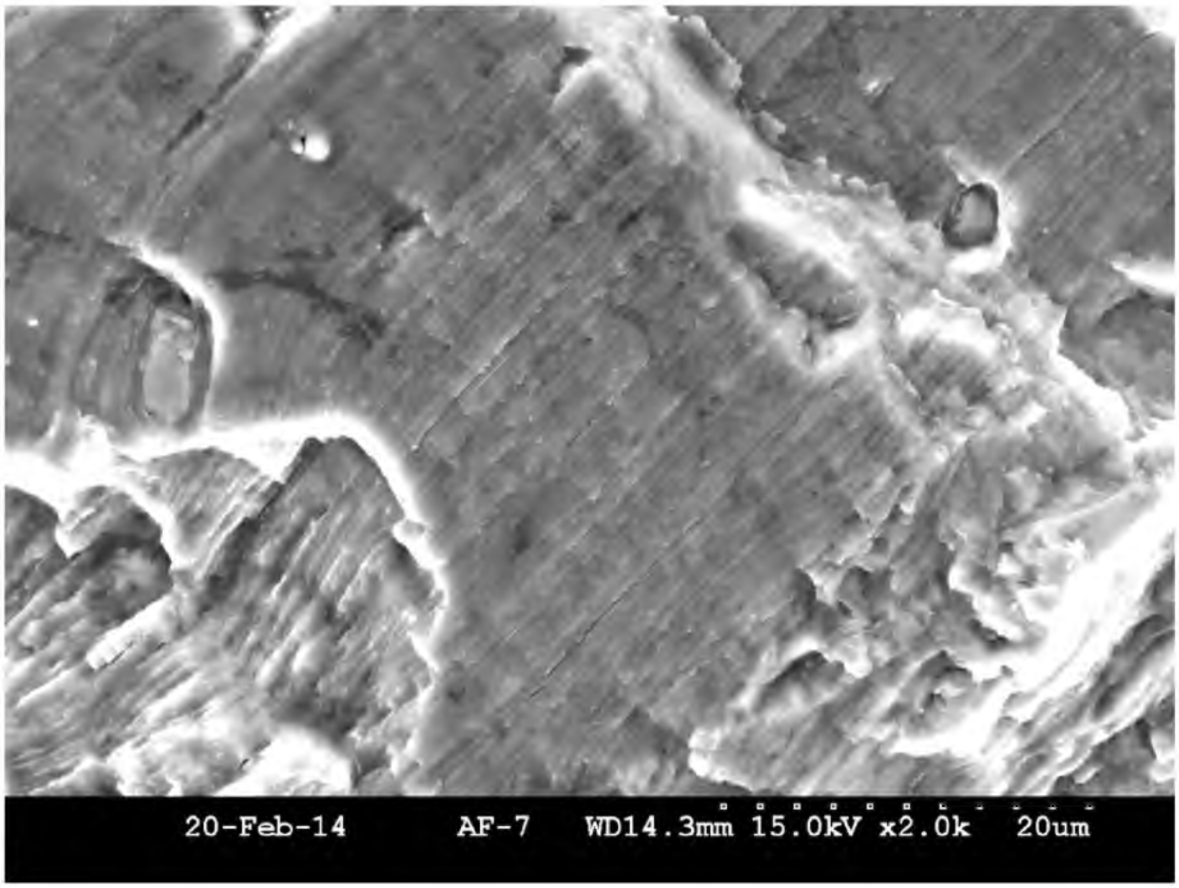
Testing Information
Test Date: Mar 17, 2014 Loading Condition: Variable Amplitude
Constant Load Rate: 100 Kips/sec Spectrum: Spectrum A+B Combination 2
Surface EDM Length: 0.0468 in Hole Diameter .250 in
Peak Stress: 27.9 ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.047		0.094			
2508	0.061		0.117			
5988	0.087		0.144			
8745	0.113		0.167			
11974	0.149		0.216			
14745	0.195		0.286			
16474	0.221		0.328			
21116	0.231		0.328			
27606	0.231		0.328			Switch to B
47549	0.231		0.337			
68879	0.231		0.337			
81852	0.237		0.337			
90133	0.246		0.337			
111212	0.281		0.341			
121940	0.296		0.349			
149728	0.341	0.227				
155010	0.349	0.257				
165341	0.374	0.292				
185822	0.415	0.328				
191861	0.431	0.370				

APPENDIX F

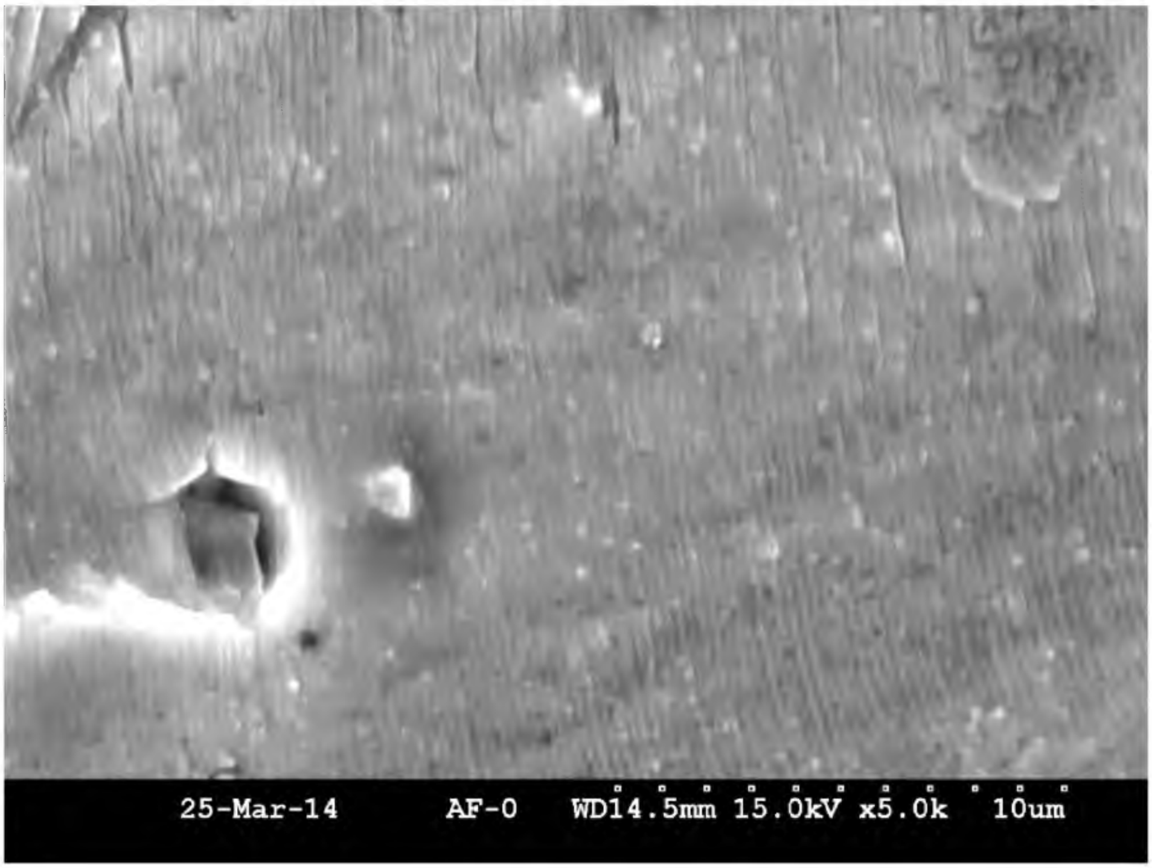
ADDITIONAL SEM IMAGES OF TEST SPECIMEN

FRACTURE SURFACES

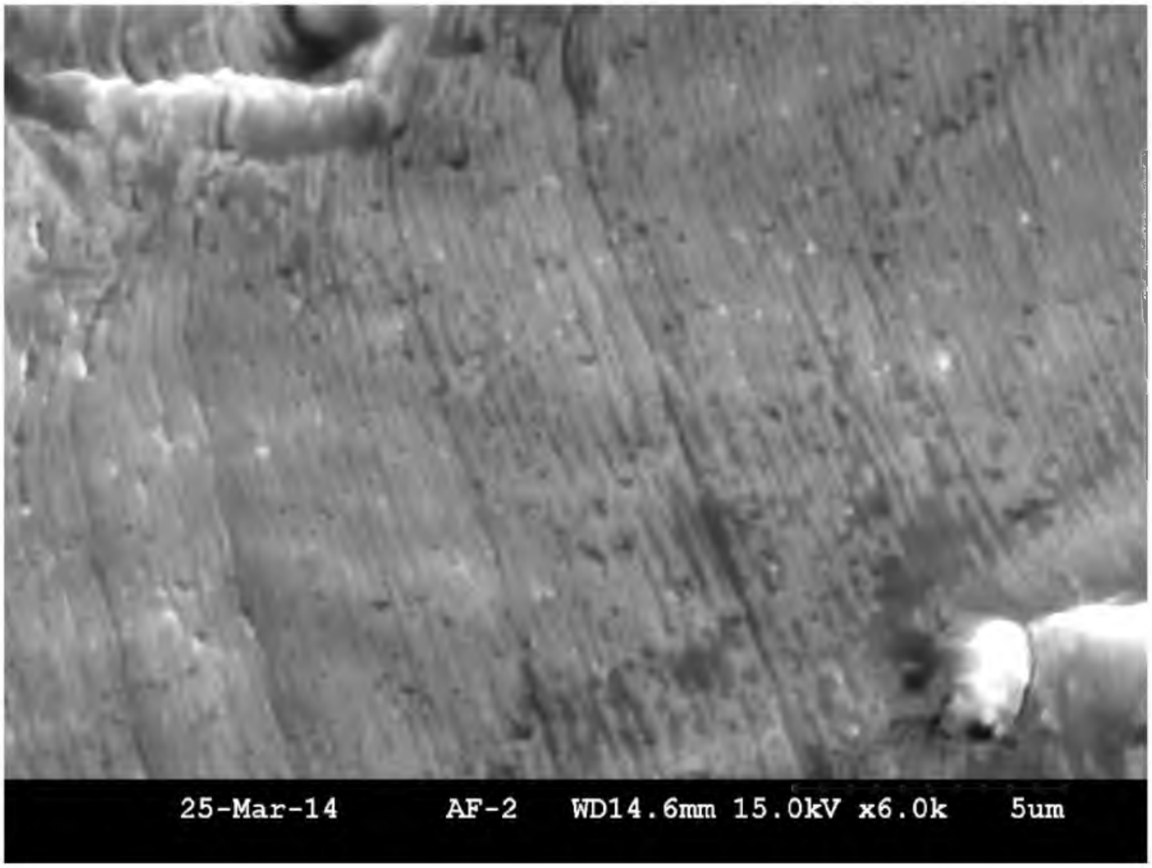


Sample 6 Spectrum B close up showing striation pattern at 2000X magnification

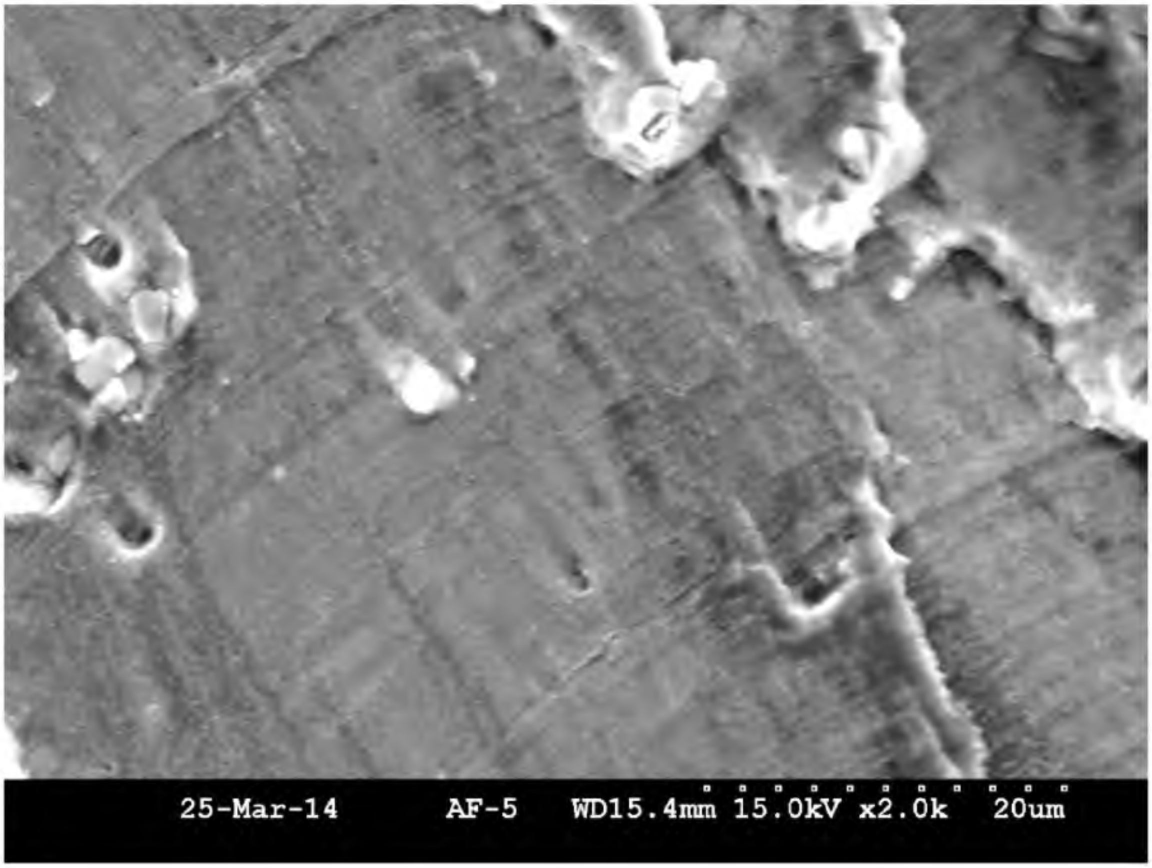
Sample 11 Photograph showing the constant amplitude fatigue striation pattern in the precrack area at 4000 X magnification



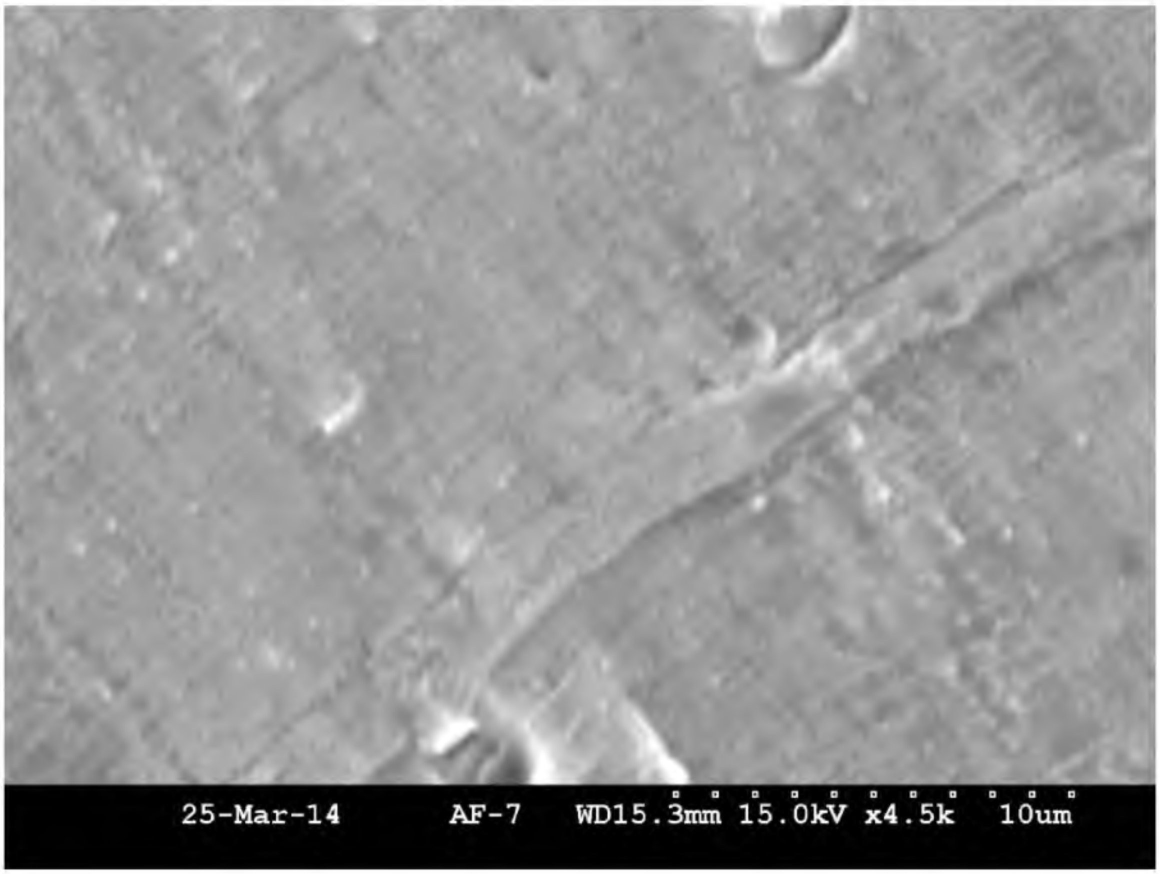
Close up photo of precrack area for Sample 11 at 5000 X magnification



Sample 11 Photo showing the Spectrum A Loading Zone Striation and peak load pattern at 6000 X magnification.



Photograph of striation pattern in Spectrum B Loading Zone at 2000X magnification



Close up showing striations from Spectrum B Loading Zone

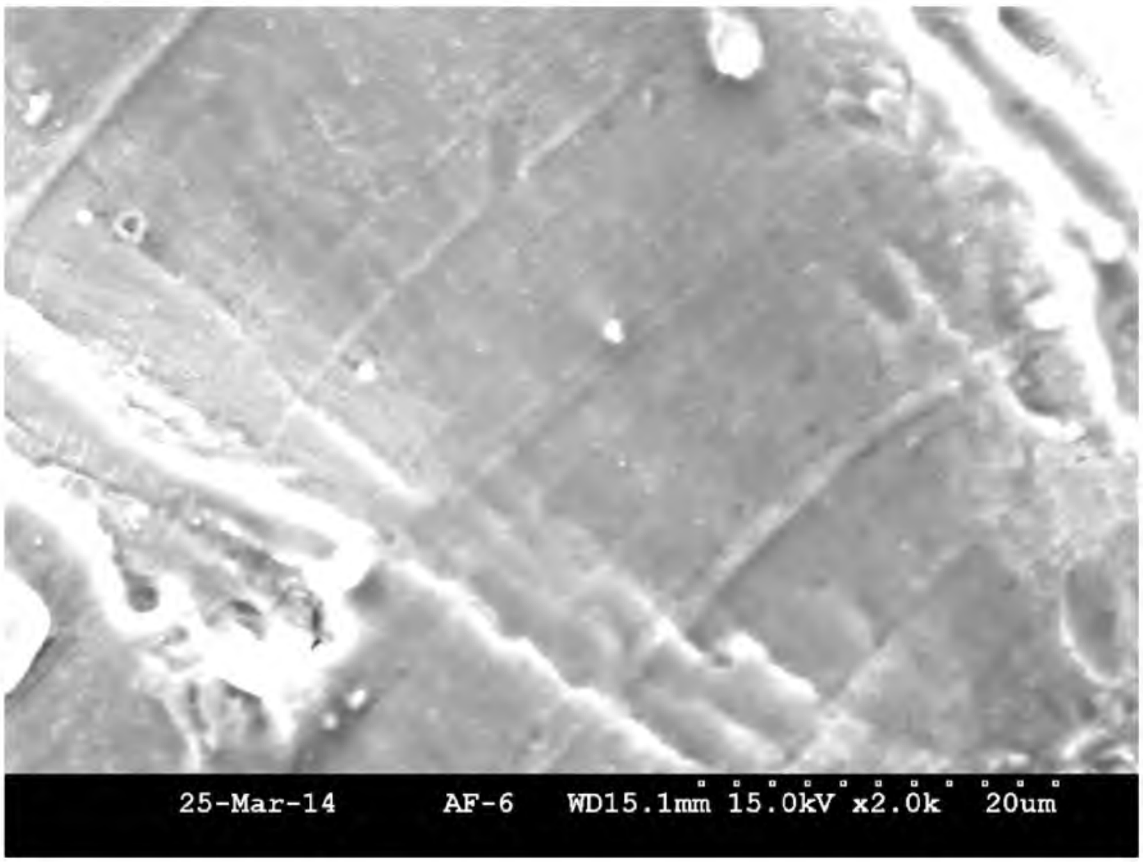
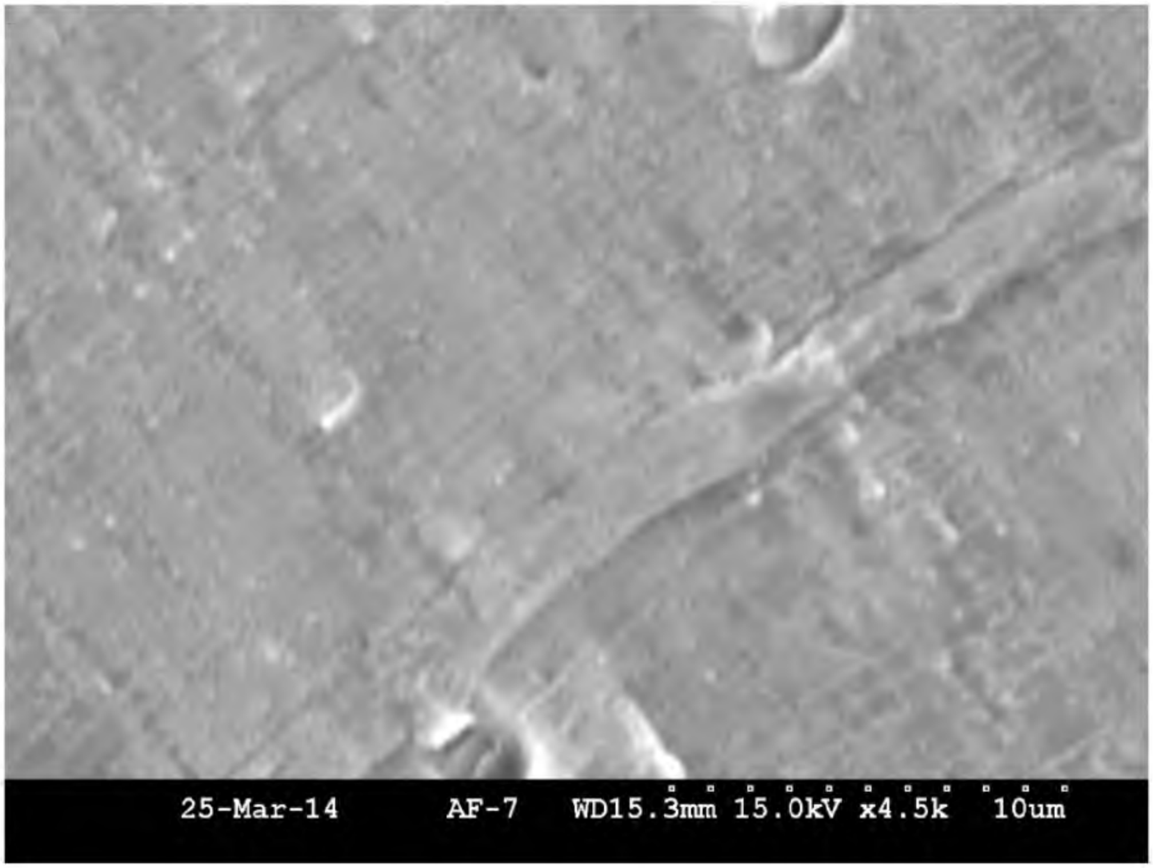
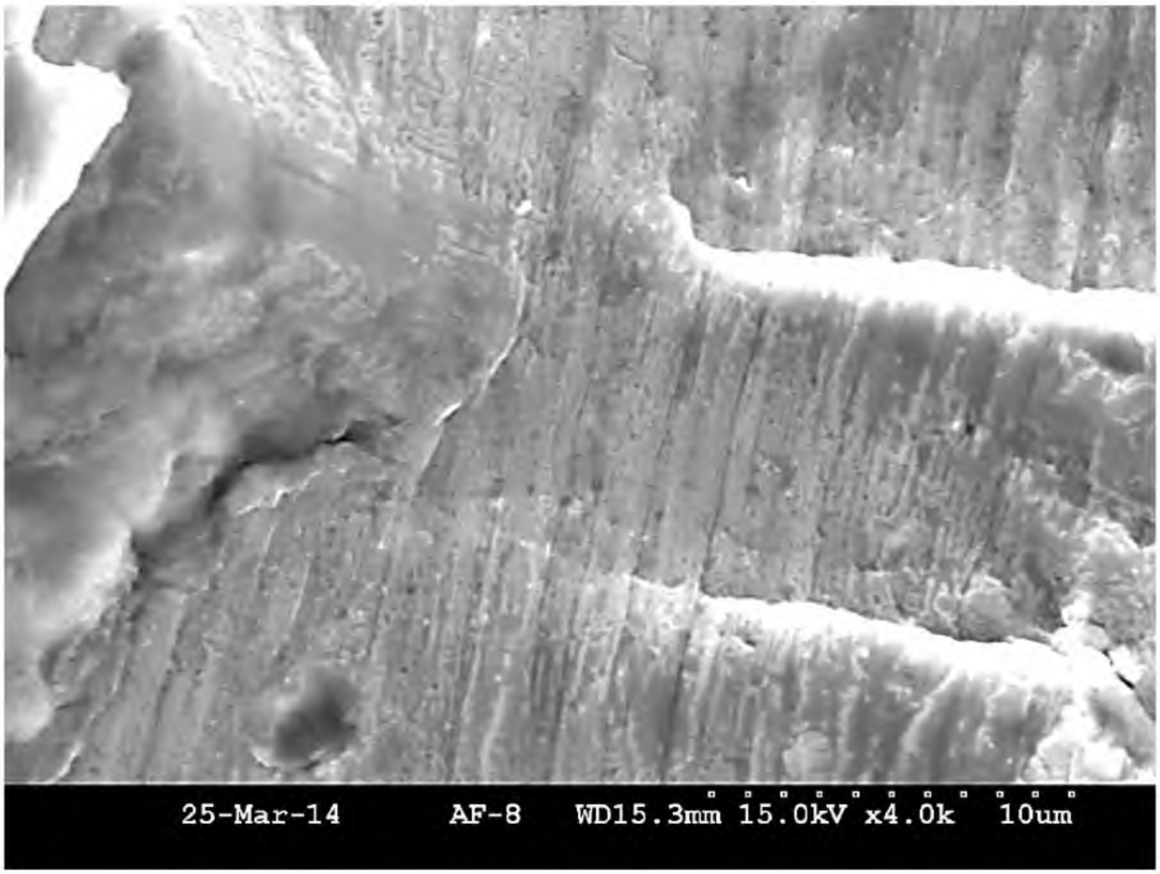


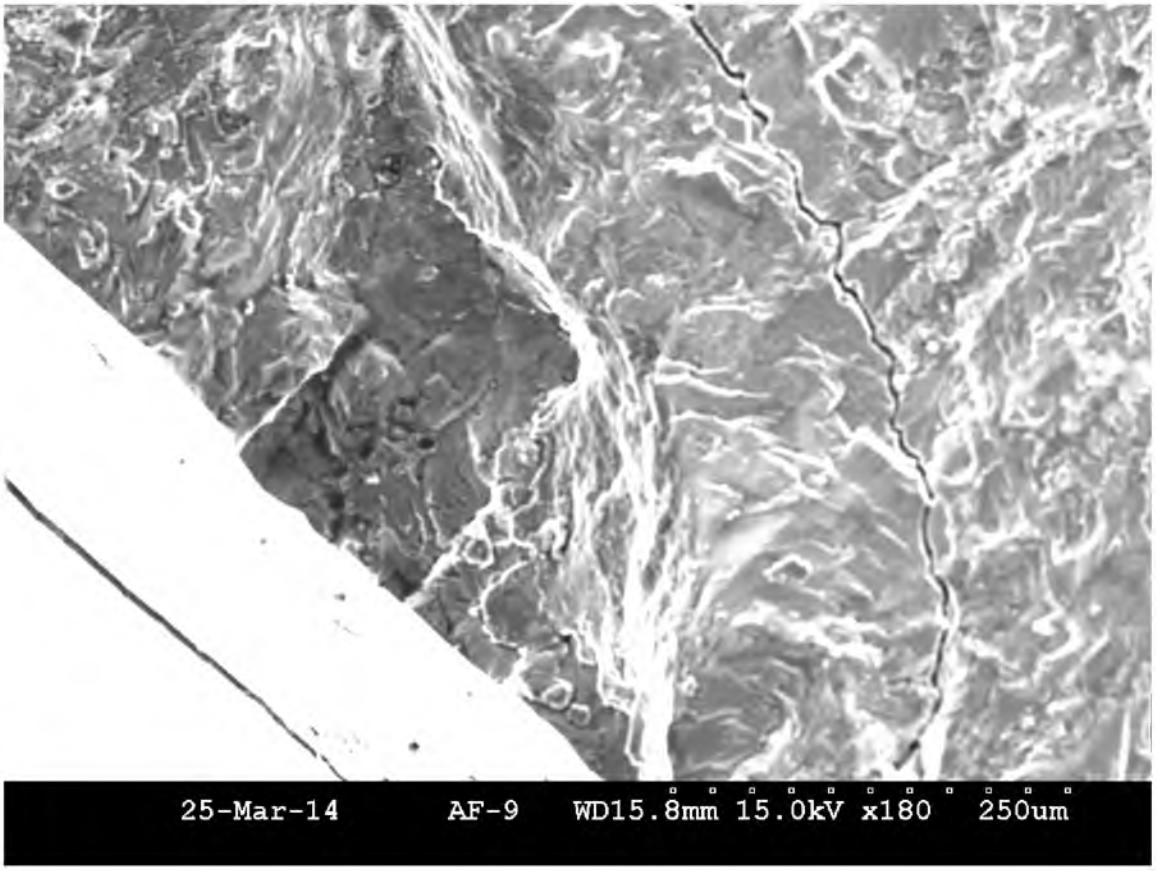
Photo showing striation pattern in Spectrum B Loading Zone for Sample 11 at 2000 X magnification



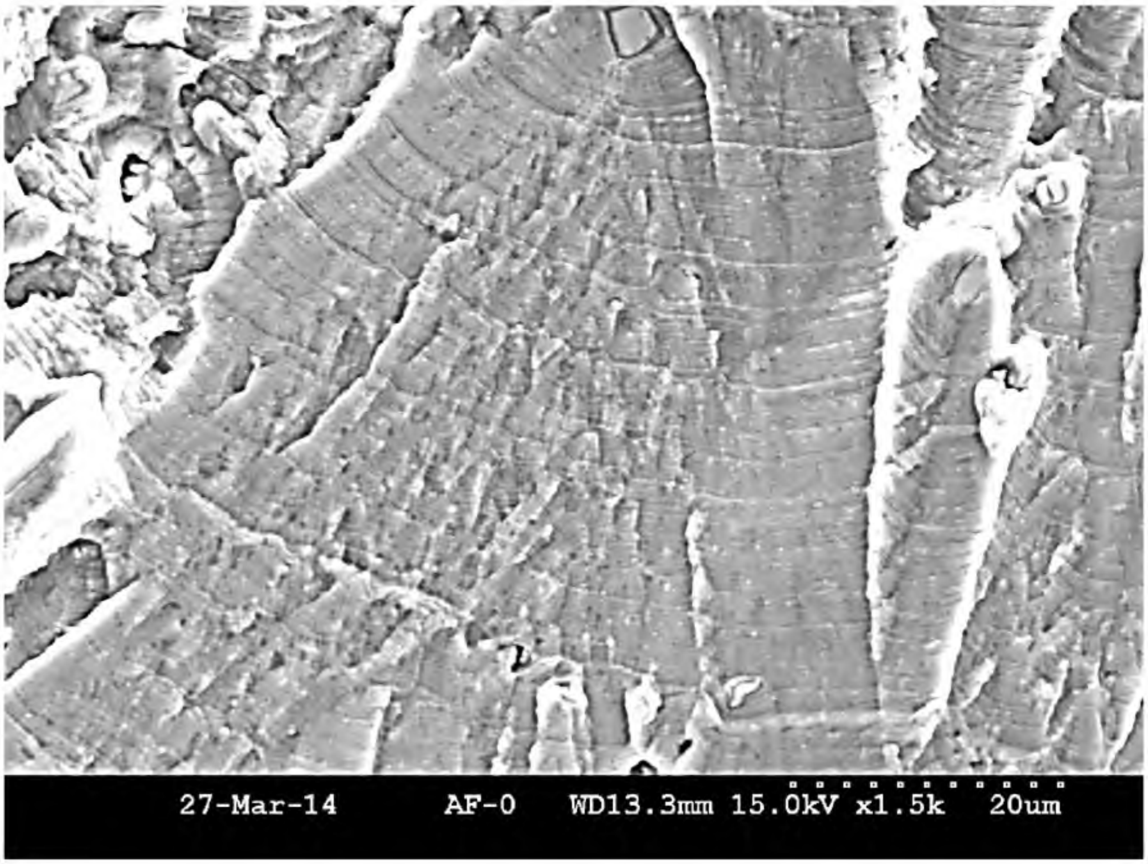
Sample 11 Close up photo of Spectrum B Loading Zone at 4500X magnification



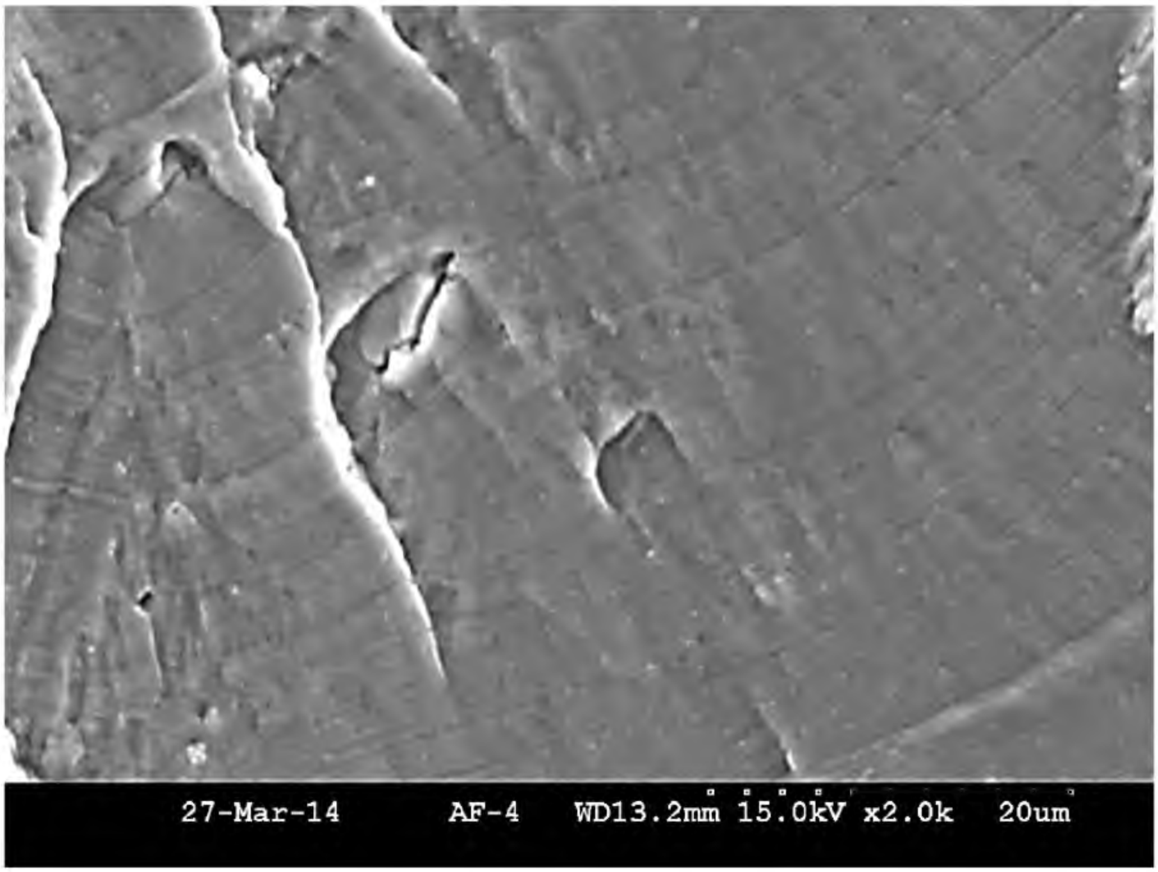
Sample 11 Close up showing striations from Spectrum B Loading Zone



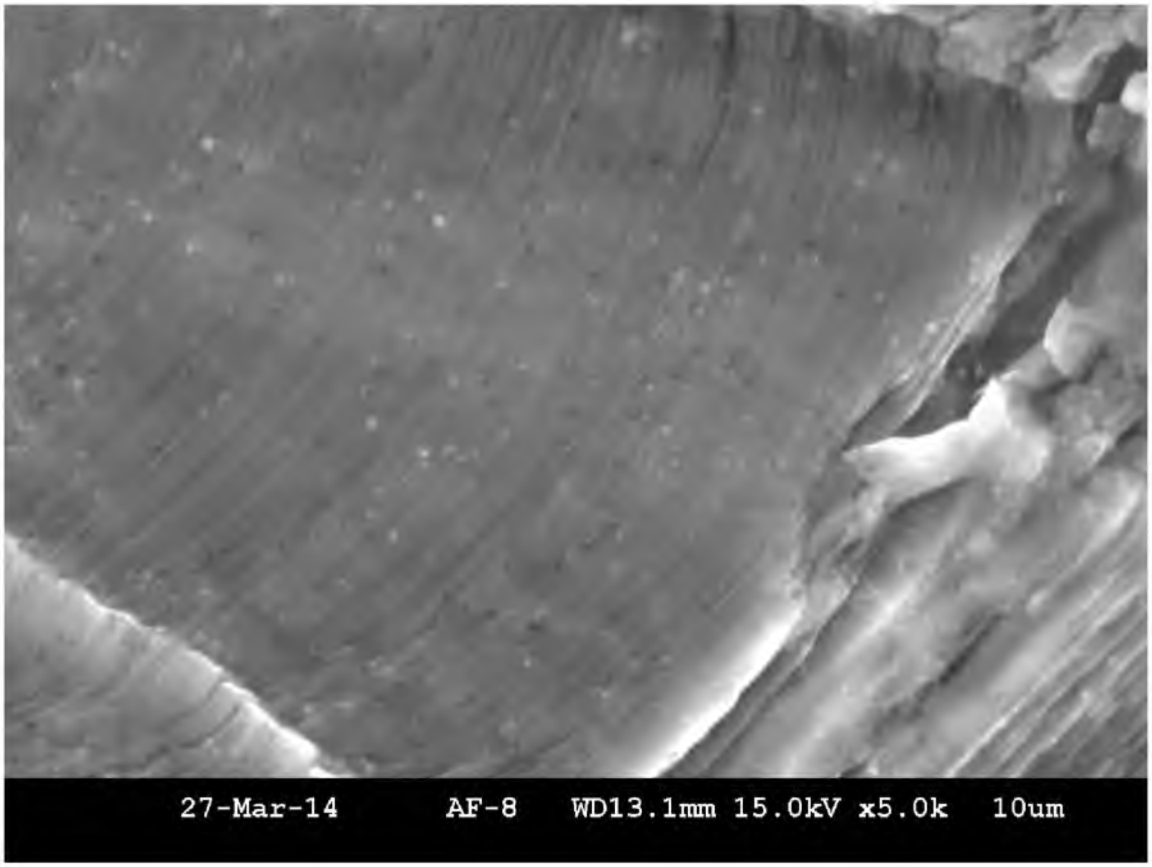
Sample 11 Photograph showing the opposite side of the bore with secondary cracking



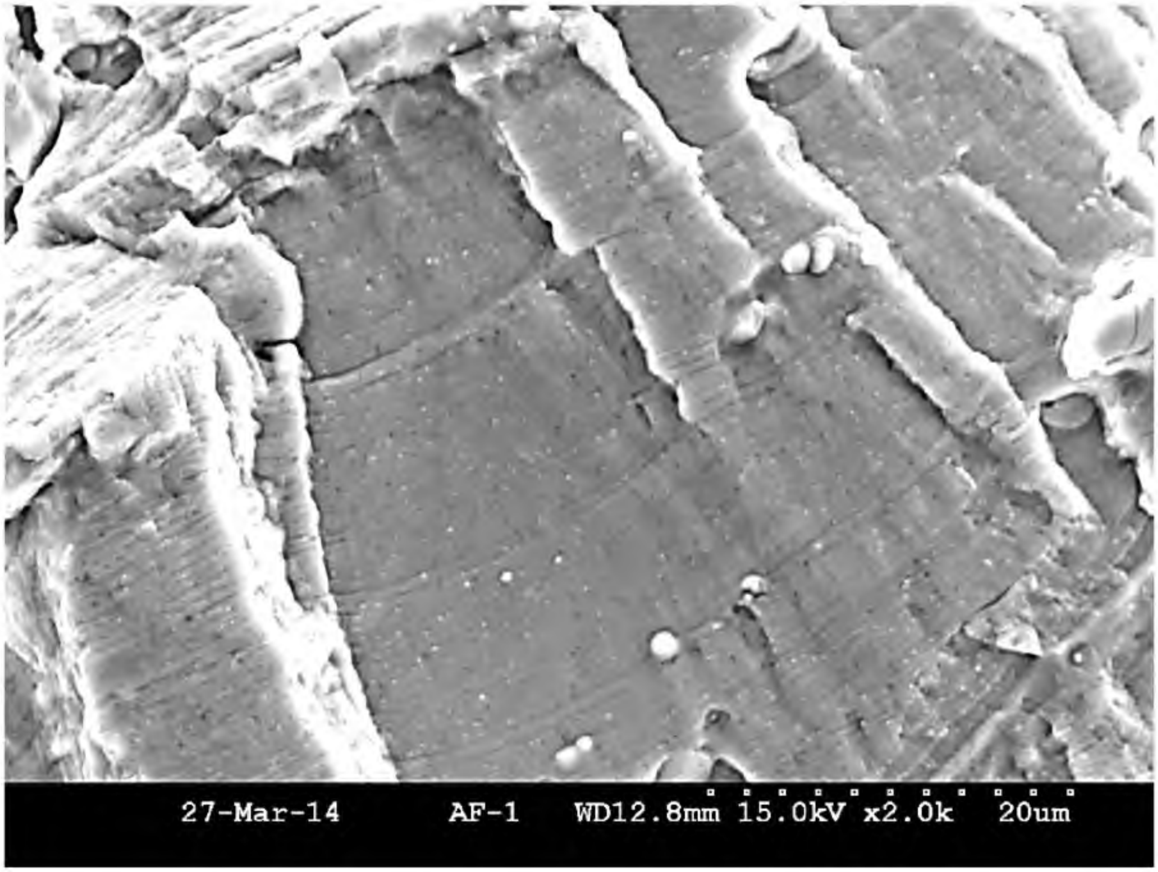
Sample 31 striation pattern under Spectrum A variable amplitude loading



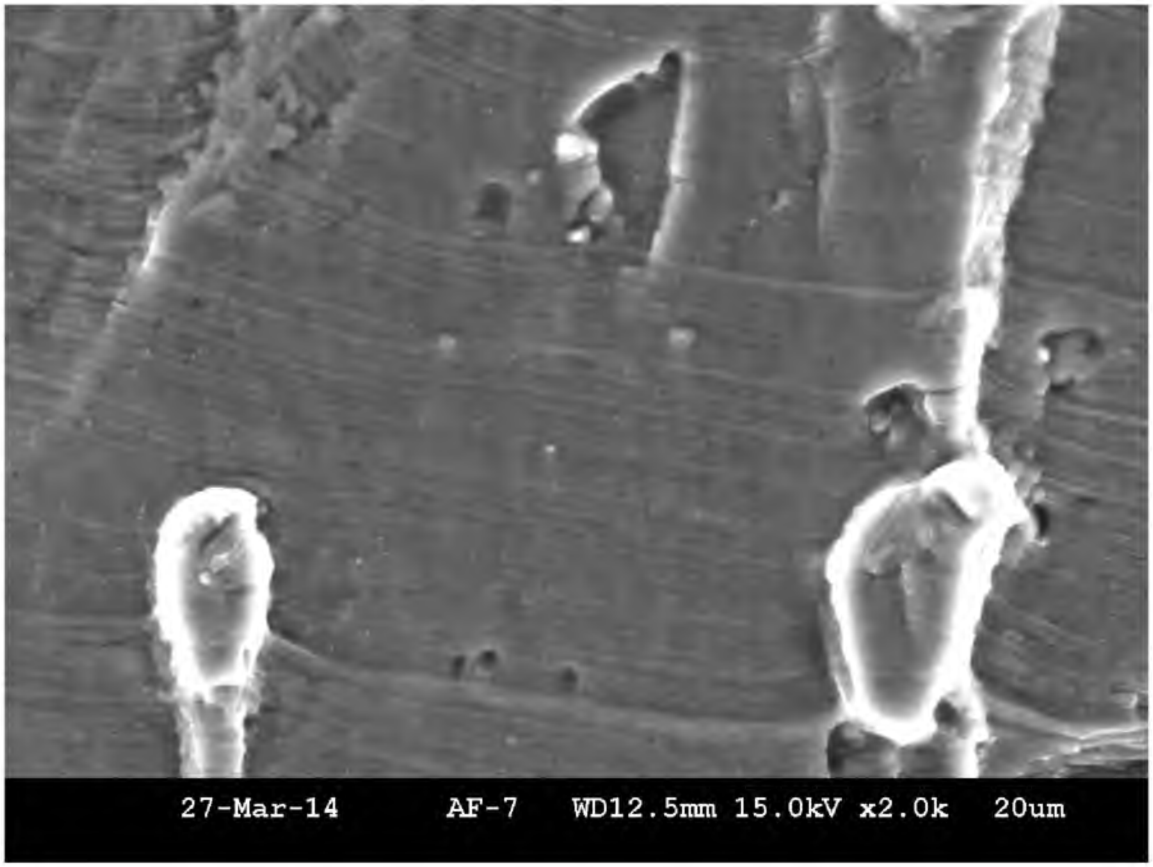
Sample 31 striation pattern under Spectrum A Load Sequence



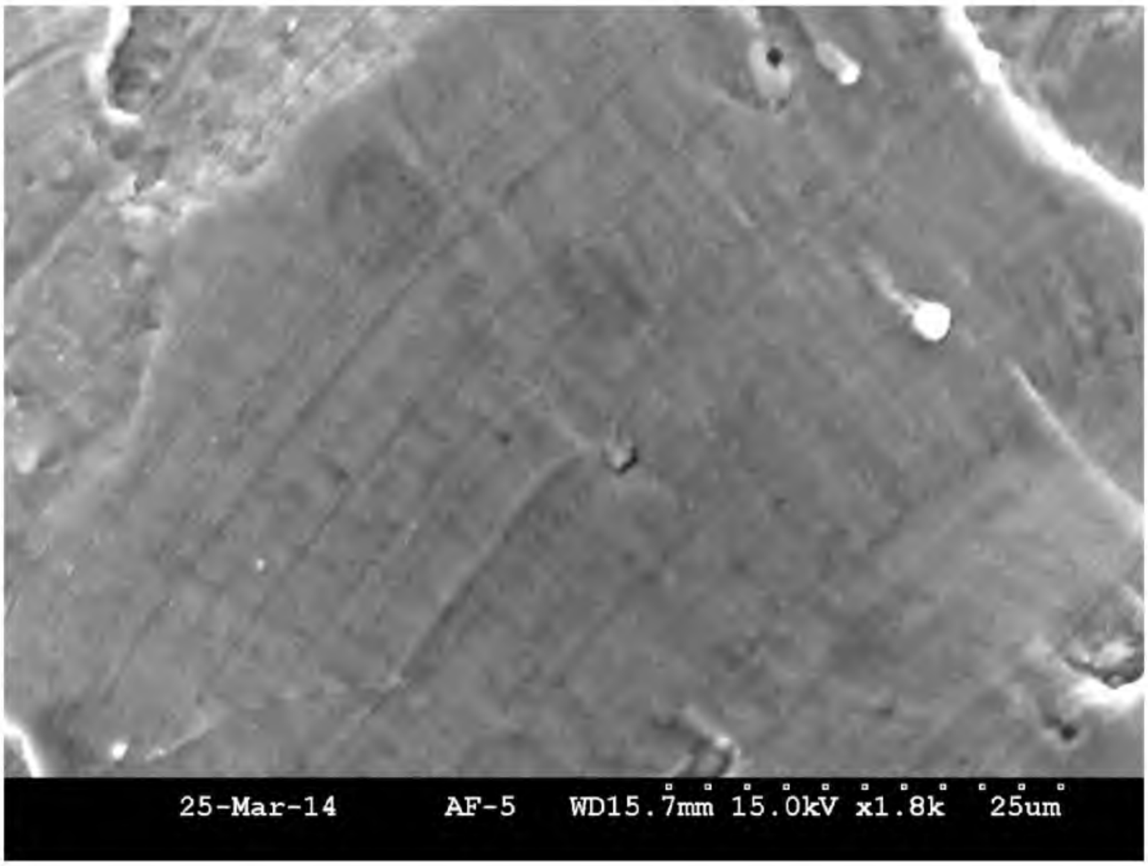
Sample 31 Spectrum B Loading area



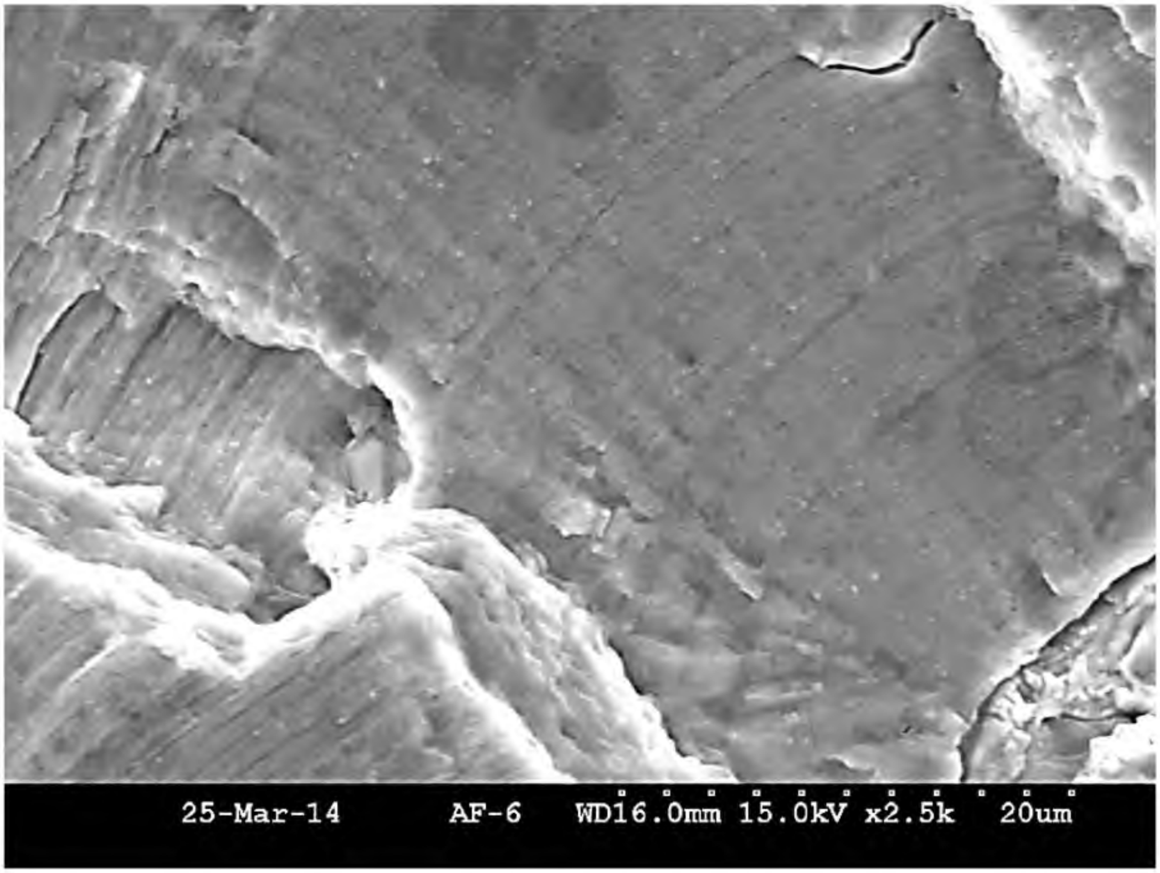
Sample 31 Spectrum B Loading Area



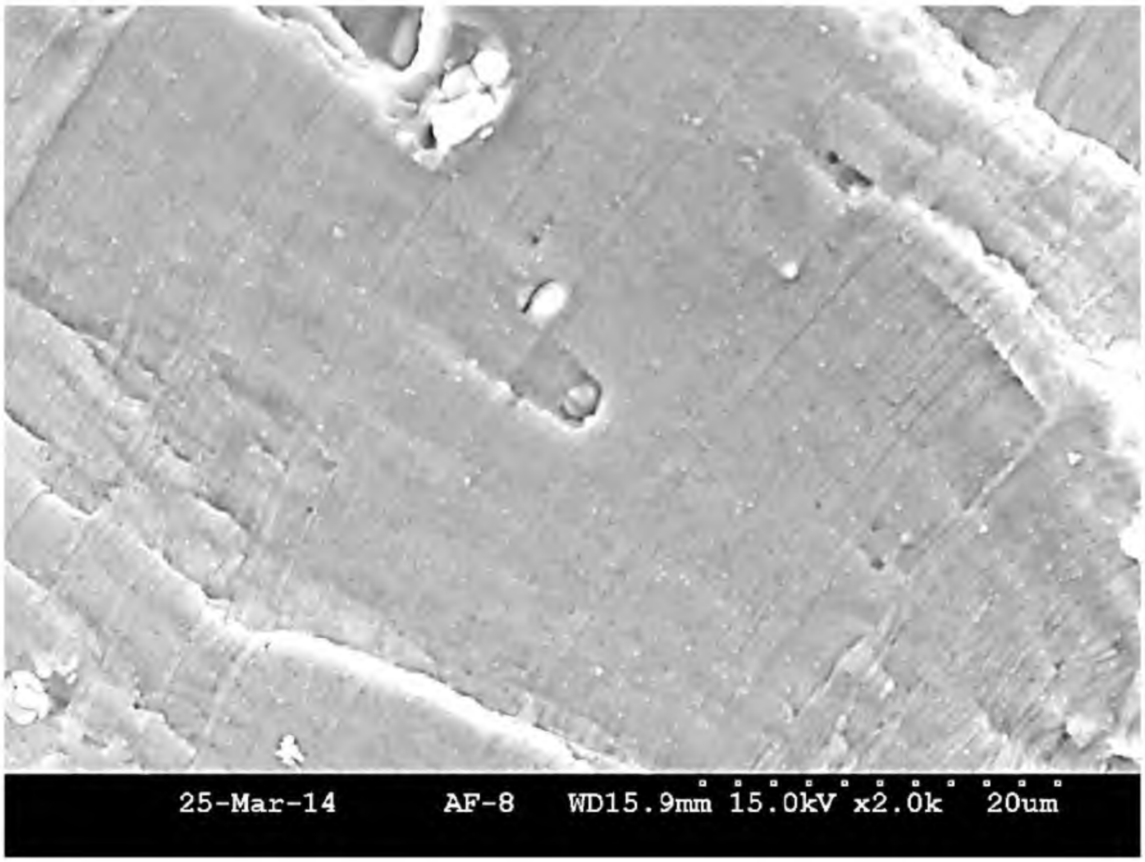
Sample 31 Spectrum A Section



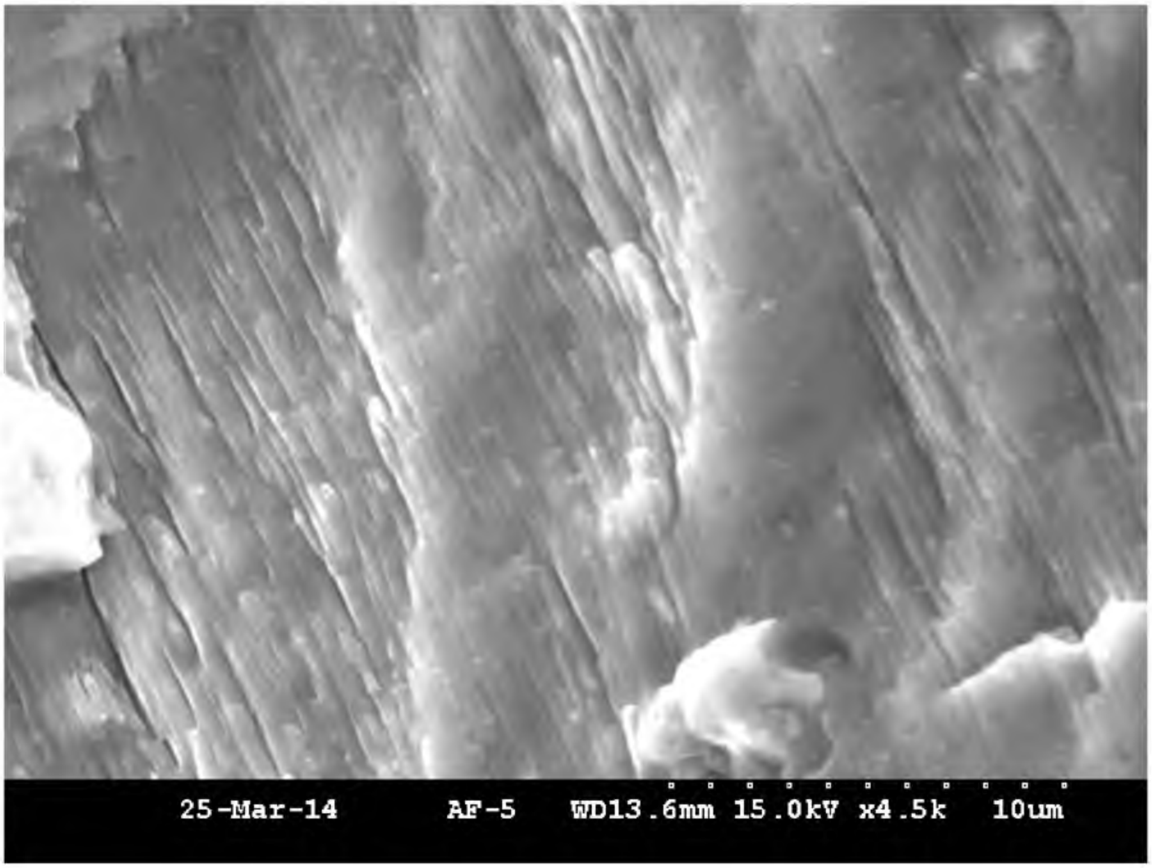
Sample 13 RPDS closeup at 1800 X magnification



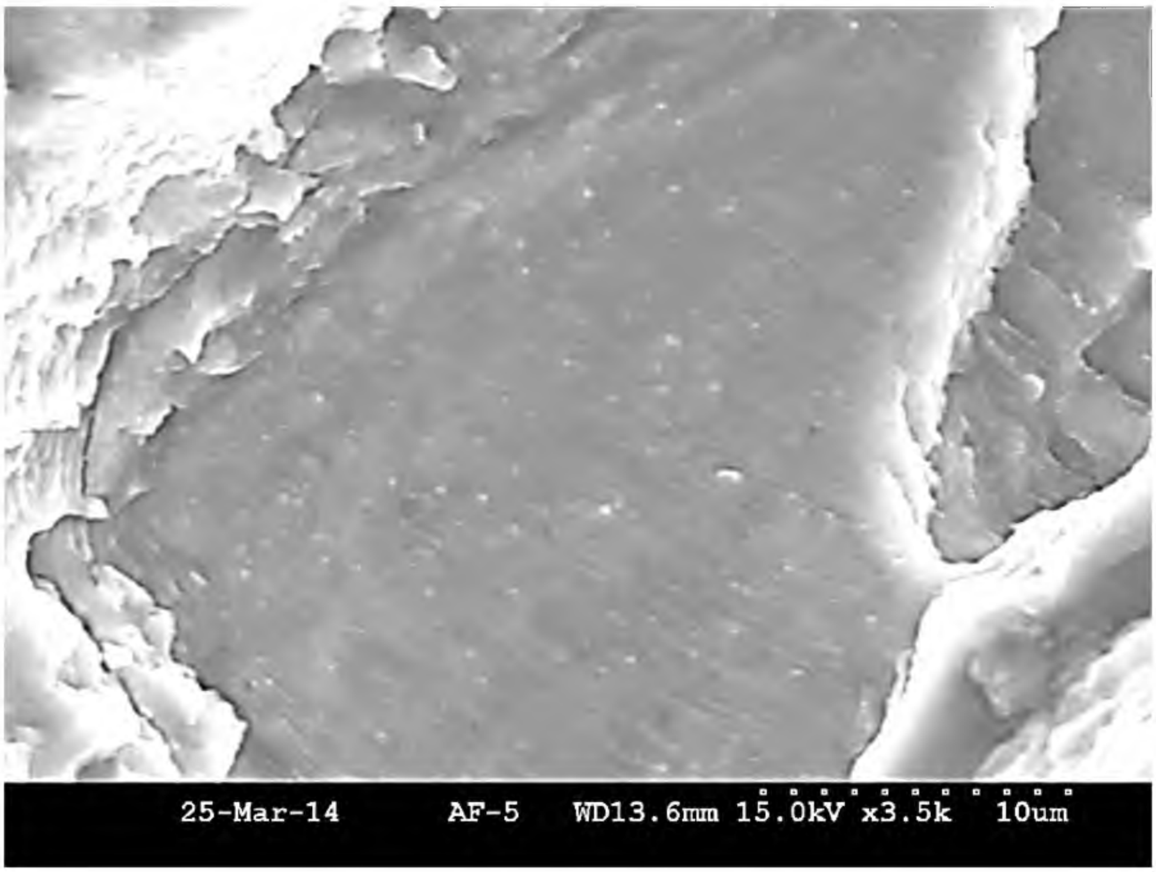
Close up of Sample 13 Spectrum A Loading Zone Striations at 2500X magnification



Sample 13 Spectrum B Loading Zone Striation Pattern at 2000 X magnification

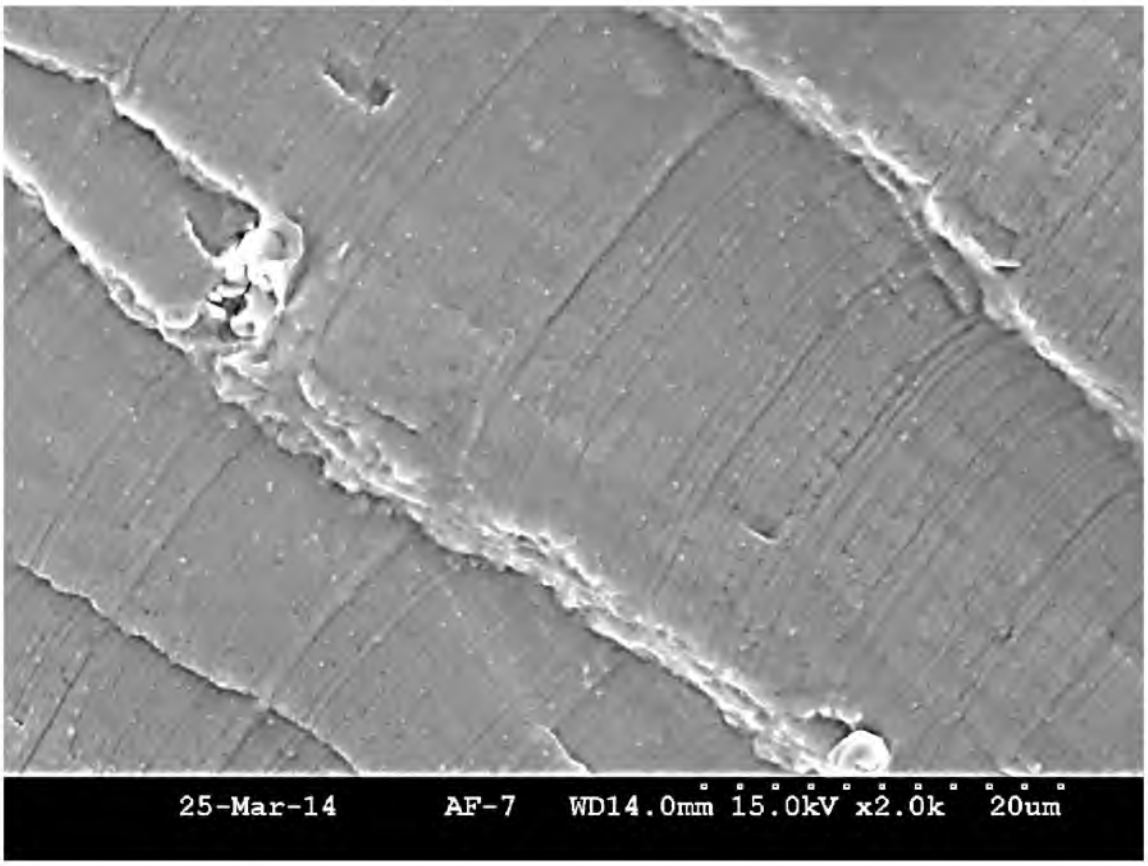


Sample 12 Precrack zone striation count showing constant amplitude loading striations

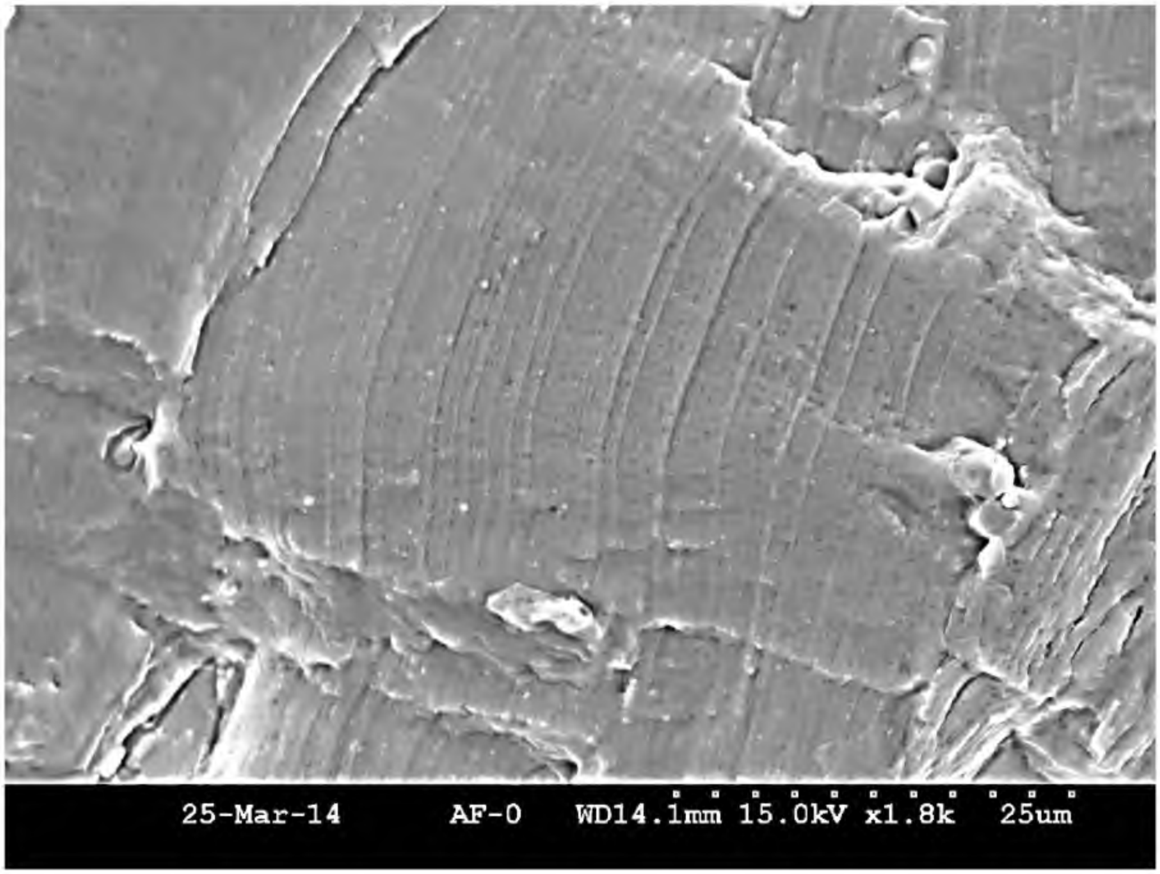


Sample 12 Close up of pre crack zone constant amplitude striations

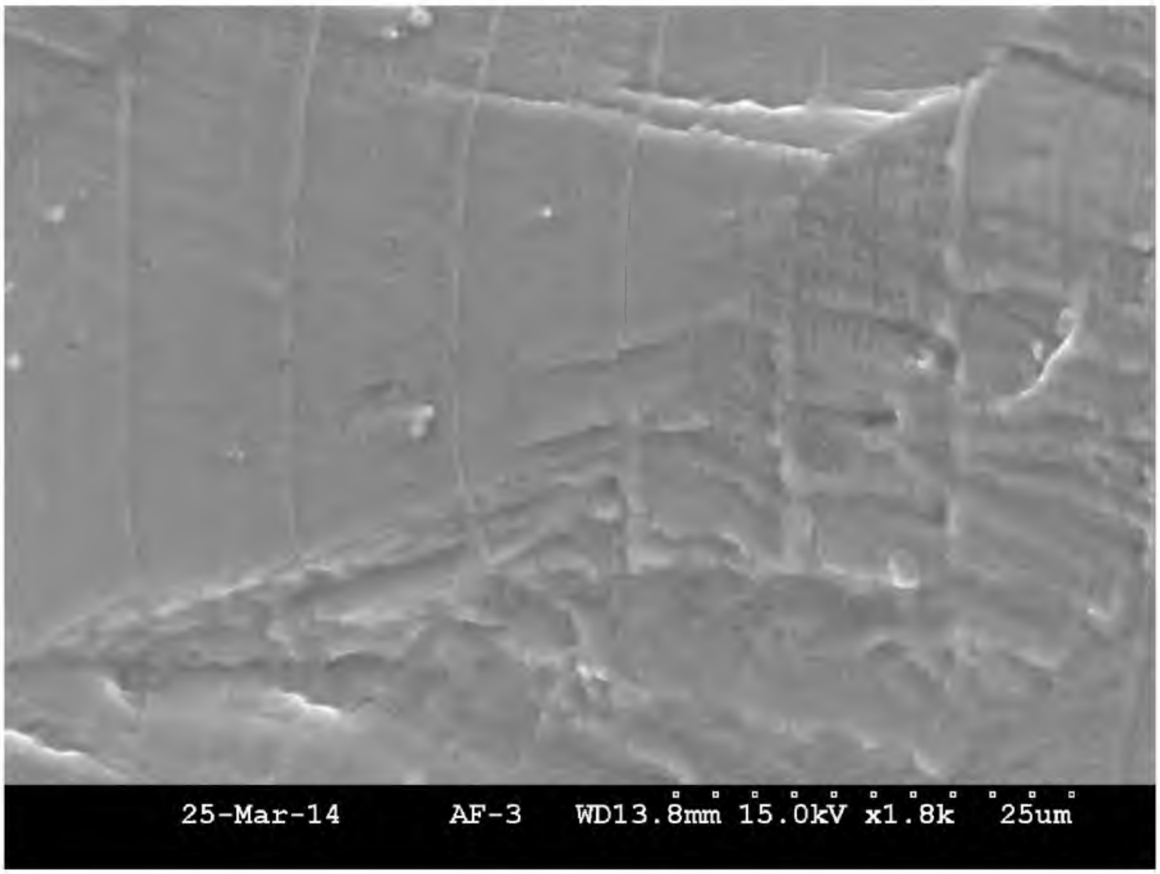
Photo showing Sample 12 striation pattern with peak loads under Spectrum A loading approximately half way down the bore



Sample 12 Spectrum A Loading striation pattern with peak loads at 2000 X magnification



Sample 12 Showing striation pattern under Spectrum B Loading at 1800 X magnification



Striation pattern under Spectrum B Loading at 1800 X magnification

Same Spectrum B area under 4000 X magnification

APPENDIX G

SEM PROCEDURES

Hitachi SEM Model S-2600N

PROCEDURE FOR USING THE SEM

1. Turn on the chiller to the SEM and wait for it to reach a temperature of 68 degrees F.
2. Turn on the power to the SEM.
3. Place the specimen in the vibrating cleaner containing a lacquer solution for 10 minutes.
4. Replace the lacquer solution with one of alcohol for another 10 minutes.
5. Release the vacuum from the observation chamber.
6. Using rubber gloves, place the cleaned specimen into the holding mount, close the chamber and turn on the vacuum pump.
7. Once the vacuum indicator signals that the conditions are sufficient, the electron beam is turned on.
8. Adjust the focus, contrast and brightness until the image is clear. Initially keep a working distance of 15 to 20 mm to obtain a wide view of the surface.
9. Pick a desired location on the surface and magnify the image to 3000X to 4000X and focus the image. This will help produce higher quality pictures at smaller magnifications.

10. Once the image is focused, zoom back out to obtain the widest view desired.
11. Progressively take pictures by incrementally increasing the magnification until the desired amount of detail is obtained.
12. Once the examinations are complete, turn off the elector beam and the pump to release the vacuum from the observation chamber.
13. Using rubber gloves, open the observation chamber and remove the specimen.
14. Close the observation chamber and turn on the pump once more. This will help prevent contaminants from entering the chamber.
15. Once the observation chamber has sufficient vacuum applied, the power may then be turned off to both the SEM and chiller.

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CHAPTER 6

SUMMARY

6.1 Conclusions

The overarching goal of this research was to obtain life predictions for 5 different spectrum loading combinations and provide the necessary justification to allow for maintenance schedule modification when temporary usage environments are encountered. A secondary goal is to provide useful data on crack tip plasticity and retardation to the fatigue and fracture community. Trying to achieve both goals to the fullest extent is beyond the scope of this effort and further research with a detailed process is necessary for fully characterizing the crack tip plasticity and retardation.

The methodology of fatigue testing representative specimens under the exact loading spectra and assessing the changes in loading on the material response at various fatigue life points is highly effective as long as all of the load frame and associated hydraulic and cooling system are fully functional. The evaluations were possible largely due to the previous fatigue crack growth data and modeling accomplished for this 2024-T351 material and for the geometry used in the experiment. For new materials and geometry configurations, sufficient fatigue growth modeling will need to be established using E647 guidelines as a reference.

This experiment showed a significant increase in inspection interval which provides economic savings while maintaining the same levels of safety of flight. Retardation models were developed for all scenarios except the Spectrum A+B Combination 3 scenario which would benefit from further research based on my Recommendations section.

6.2 Significance

This experiment contributes to the field of fatigue and fracture mechanics by developing a methodology to assess the material response effect of various spectrum combinations. It provides the analyst the ability to assess actual spectrum loading conditions and update damage tolerance life prediction models for a change in spectrum loading. This provides the structural engineer and analyst working on a product in service the ability to assess the change in loading environment that should be reflected in a change to the inspection interval. This is very beneficial for military aircraft that are deployed and loaded under a benign spectrum, in that the maintenance inspection interval can be adjusted to allow for keeping the aircraft longer in theatre without bringing it back for NDI of critical fatigue locations. Furthermore, this method allows for characterizing the residual strength condition when the aircraft is returned to the original loading condition upon rotating out of theatre missions to stateside training. For the designer, this method allows for analyzing the effect of several spectrum options for material selection and for life prediction models.

6.3 Recommendations

1) It was an important lesson learned in this research that to conduct an effective fatigue crack growth study, the entire system needs to be understood and functioning. This system includes the hydraulic system, the cooling system, electrical power supply, load frame and controller system and software which need to be considered and evaluated for suitable service. It is highly recommended that adequate time be spent to ensure Quality Control steps be established for the entire system.
2) Acquire or develop cameras, still or video, that can be incorporated into the travelling microscope to capture focused images of the crack front for reporting purposes.
3) Conduct further research with an expanded matrix to develop the life limit in which a change in spectrum shows no impact. This research should involve running the coupons to full fracture to better estimate the retardation effects.
4) Conduct further micro research using the SEM to characterize the local retardation effects due to overloads and underloads.
5) Include more replicates per combination based on Design of Experiments to assess the variability of the process.
6) Upgrade AFGROW modelling to allow load history and plastic zone effect to transfer from one spectrum loading profile to another.
7) If a product is expected to experience temporary changes in loading environment that are on the order of 10% of the total expected service

objective or greater, provisions should be made to assess these environments in the context of maintenance scheduling.

APPENDIX A

TEST SPECIMEN MATERIAL CERTIFICATION SHEETS

Aero Specialties Material Corp.
20 Burt Drive
Deer Park, NY 11729
USA

Voice: 631-242-7200
Fax: 631-242-7652

PACKING SLIP

Invoice Number: 15540
Invoice Date: Oct 23, 2012
Page: 1

Sales Order Number: N5090-DL

Bill To:	Ship to:
NORTHROP GRUMMAN 925 SO. OYSTER BAY ROAD M/S U03-26 BETHPAGE, NY 11714	NORTHROP GRUMMAN TECH SVC. 925 SOUTH OYSTER BAY ROAD ATT: KEVIN COOK BETHPAGE, NY 11714

Customer ID	Customer PO	Sales Order
NORTHR	TA2086004	N5090-DL
Sales Rep ID	**Shipping Method**	**Payment Terms**
DONNA	ROBLIS	Prepaid

Order Qty	Item	Item Unit	Description	Shipped Qty
40.00	2024-T351 .500"THK.	EA	2024-T351 QQA-250/4 .500 X 4.250" X 16.250" GRAIN W/16.250" DIM	40.00
1.00	PO#	<Each>	LOT# 566454A5	1.00
1.00	FREIGHT CHGS	<Each>	FREIGHT CHARGES PREPAID ON THE ABOVE REFERENCED PO.	1.00

Certificate of Compliance

his is to certify that the material supplied against the above purchase order has been produced in accordance with applicable specifications

D-Donna

Certification Clerk

AERO SPECIALITIES CERTIFY THIS IS
A TRUE COPY OF THE MILL TEST
REPORT - USED TO FILL YOUR ORDER.
Company Northrop Grumman
PO# TA2086004
Our Order # 05090 SI
QTY 40 EA
Q.C. asst. [illegible]
Authorized Signature

KAISER ALUMINUM
Trentwood Works - Spokane, WA 99215
Phone: (800) 367-2586

CERTIFIED TEST REPORT

Serial Number
4244600

CUSTOMER PO NUMBER:	WORK PACKAGE:	CUSTOMER PART NUMBER:	SHIP RUN/LOAD:	GOV'T CONTRACT NUMBER:
029386			102176/5	

KAISER ORDER NO:	LINE ITEM:	SHIP DATE:	ALLOY:	CLAD:	TEMPER:	PRODUCT DESCRIPTION:
1121561	3	9-NOV-2011	2024	BARE	T351	Sawed Plate

WEIGHT SHIPPED:	QUANTITY:	B/L NUMBER:	GAUGE:	DIAMETER/WIDTH:	LENGTH:
8026 LB	18 PCS EST.	2034449	0.5000 IN	60.500 IN	144.500 IN

MHU 1539302: LOT 566454A5: 11 pieces;
MHU 1539304: LOT 566454A5: 7 pieces;

Certified Specifications

AMS 4037/RevN   AMS-QQ-A-250/4/RevA   ASTM B 209/Rev10

Test Code: 1504

Test Results

Lot: 566454A5 **Cast 548** **Drop 01** **Ingot 3** **Melted in USA**

(ASTM E8/B557)
(EN 2002-1)

Tensile:	Temper	Dir / # Tests	Ultimate KSI (MPA)	Yield KSI (MPA)	Elongation %
	T351	LT / 2 (Min:Max)	67.4 : 67.5 (465 : 465)	44.4 : 44.8 (306 : 309)	20.0 : 20.1

(ASTM E1251)

Chemistry:	SI	FE	CU	MN	MG	CR	ZN	TI	V	ZR		OTHER
Actual	0.07	0.16	4.5	0.58	1.4	0.01	0.12	0.01	0.01	0.00	TOT	0.03

ALLOY LIMITS

2024	SI	FE	CU	MN	MG	CR	ZN	TI	V	ZR	OTHER	MAX
MIN	0.00	0.00	3.8	0.30	1.2	0.00	0.00	0.00	0.00	0.00	EACH	0.05
MAX	0.50	0.50	4.9	0.9	1.8	0.10	0.25	0.15	0.05	0.05	TOT	0.15

Aluminum Remainder

KAISER ALUMINUM
Trentwood Works - Spokane, WA 99215
Phone: (800) 367-2586

CERTIFIED TEST REPORT

Serial Number
4244600

CERTIFICATION

KAISER ALUMINUM FABRICATED PRODUCTS, LLC (KAISER) HEREBY CERTIFIES THAT METAL SHIPPED UNDER THIS ORDER WAS MELTED IN THE UNITED STATES OF AMERICA OR A QUALIFYING COUNTRY PER DFARS 225.872-1(a), WAS MANUFACTURED IN THE UNITED STATES OF AMERICA, AND MEETS THE REQUIREMENTS OF DFARS 252.225 FOR DOMESTIC CONTENT. THIS MATERIAL HAS BEEN INSPECTED, TESTED, AND FOUND IN CONFORMANCE WITH THE REQUIREMENTS OF THE APPLICABLE SPECIFICATIONS AS INDICATED HEREIN. ALL METAL WHICH IS SOLUTION HEAT TREATED COMPLIES WITH AMS 2772. ANY WARRANTY IS LIMITED TO THAT SHOWN ON KAISER'S STANDARD GENERAL TERMS AND CONDITIONS OF SALE. TEST REPORTS SHALL NOT BE REPRODUCED EXCEPT IN FULL, WITHOUT THE WRITTEN APPROVAL OF KAISER ALUMINUM FABRICATED PRODUCTS, LLC LABORATORY. THE RECORDING OF FALSE, FICTITIOUS, OR FRAUDULENT STATEMENTS OR ENTIRES ON THE CERTIFICATE MAY BE PUNISHED AS A FELONY UNDER FEDERAL LAW. ISO-9001:2000 CERTIFIED.

Mike Klocke

MIKE KLOCKE, LABORATORIES SUPERVISOR

TECHNICAL SERVICES LABORATORY Northrop Grumman Corporation 925 South Oyster Bay Road, M/S U03-26 Bethpage, New York 11714-3582	LABORATORY REQUEST NUMBER 37304-12 DATE 10/29/2012

DIRECTED TO: (√) ☐ CHEMISTRY LABORATORY ☒ METALLURGY LABORATORY ☐ ADV-DEV TECH-OPS ☐ NDT LABORATORY ☐ OPERATIONS

PART NAME/PART NUMBER : A-10 –IV 3.3.5 Crack Growth (Option 1) For Drawing GT270KB003

TYPE OF MATERIAL: 2024-T351 Aluminum Plate (.50 Thick)

PROGRAM	PURCHASE ORDER NO.	JOB NUMBER/IOS	QUANTITY	Lot NO.
A-10				418964A3

SPECIFICATIONS	SELLER OR CUSTOMER
AMS QQ-A-250/4	

TYPE OF TEST OR ANALYSIS REQUIRED
Mechanical Properties of an A-10 IATP Control Points Test Material

PURPOSE OF TEST/BACKGROUND

SAMPLE DESCRIPTION/CONDITION/REMARKS

REQUESTED BY	MAIL STA.-BLDG	FAX	PHONE	LAB APPROVAL
Ken Grube/ Bob Fidnarick	Plant 26		516.346.9232	*John Callori*

FINDING OR RESULTS
THE ABOVE MATERIAL IS (√) ☒ **SATISFACTORY** ☐ UNSATISFACTORY ☐ INFORMATION ONLY

REMARKS:

Properties (Longitudinal)	Test Results				Requirements, min. (Longitudinal)
Specimen Number	1	2	3	AVG	
Tensile Strength, ksi	68.3	68.5	69.3	68.7	64.0
Yield Strength, ksi	57.2	57.4	57.5	57.4	42.0
% Elongation in x 2 inches	16.5	16.5	16.5	16.5	12.0

Al Sinowitz
SIGNATURE

Kevin Cook
APPROVED

(TECHNICAL SERVICES LABORATORY FAX 516-575-9909)
All Signatures on File
FORM 1512 REV. May 11
REFERENCE NO.

Lawrence Ripak Co., Inc.

Certification

Order No.: 287455 - 274440
Date: 11/27/2012
Entry Date: 11/20/2012
Page: 1 of 1

To: NGRUMNY
NORTHROP GRUMMAN
925 South Oyster Bay Rd
M/S U03-26
Bethpage NY 11714-3582

Purchase Order No.: 50712
Packing List No.:

We are pleased to provide you with the following Certification

Quantity	Part Number / Part Name / Part Description	Pounds
33	GT270KB003-11 MAT: 2024-T3511	

Process Steps

Step: 1 **Process: Sp** **Equipment #:**

Comment: Note: Certification is void if material removal exceeds 10% of nominal Almen A intensity.
Shot Peen per AMS2430 Rev S (s/s AMS-S-13165 Rev A) Machine #: 1 OD Shot: ASR230 Hardness: 45-52Rc Coverage: 100% Intensity: .010-.014A2 Actual: .0120A2 Technique Card: GT270KB003-11 REV N/C 11-26-12

Step: 2 **Process: Cl** **Equipment #:**

Acid clean per AMS2430 Rev S (s/s AMS-S-13165 Rev A) to remove shot peen residue Nitric Acid clean to remove shot peen residue

We certify that the processes listed have been performed in accordance with the specifications shown. Records are being maintained and are available for review.

D Castellano
Deborah Castellano
Planning/Cert Supervisor
Lawrence Ripak Co., Inc.

WESTPRO LAB
WWW.WESTPROLAB.COM

WESTERN PROFESSIONAL, INC.
3460 BRADY CT. NE
SALEM, OR 97301
PHONE (503)585-6263
FAX (503)585-6577
www.westprolab.com

ULTRASONICS / PHASED ARRAY / EDM
RESEARCH & DEVELOPEMENT

CUSTOMER: NORTHRUP GRUMMAN IT
P.O. #: 7500109901
S/N: PLATES 1 THRU 33
SIZE: 16" X 4" X .410"
HEAT #: UNKNOWN
MATERIAL: 2024-T351 ALUMINUM
DWG#: GT270KB003
DATE: 12-3-12

A-10 TRAINING VS NON-TRAINING MISISON
SPECTRA TEST SPECIMEN

PLATE #	DEPTH	LENGTH	WIDTH	TYPE
1	.0200"	.0301"	.0044"	CORNER NOTCH
2	.0187"	.0310"	.0046"	CORNER NOTCH
3	.0207"	.0307"	.0046"	CORNER NOTCH
4	.0200"	.0306"	.0047"	CORNER NOTCH
5	.0205"	.0309"	.0046"	CORNER NOTCH
6	.0194"	.0313"	.0045"	CORNER NOTCH
7	.0202"	.0310"	.0044"	CORNER NOTCH
8	.0203"	.0309"	.0048"	CORNER NOTCH
9	.0206"	.0306"	.0045"	CORNER NOTCH
10	.0211"	.0312"	.0044"	CORNER NOTCH
11	.0205"	.0298"	.0045"	CORNER NOTCH
12	.0204"	.0307"	.0046"	CORNER NOTCH
13	.0206"	.0313"	.0045"	CORNER NOTCH
14	.0204"	.0322"	.0048"	CORNER NOTCH
15	.0198"	.0324"	.0044"	CORNER NOTCH
16	.0208"	.0315"	.0046"	CORNER NOTCH
17	.0206"	.0323"	.0044"	CORNER NOTCH

PLATE #	DEPTH	LENGTH	WIDTH	TYPE
18	.0197"	.0323"	.0047"	CORNER NOTCH
19	.0204"	.0304"	.0046"	CORNER NOTCH
20	.0202"	.0298"	.0047"	CORNER NOTCH
21	.0211"	.0313"	.0045"	CORNER NOTCH
22	.0210"	.0317"	.0046"	CORNER NOTCH
23	.0199"	.0317"	.0048"	CORNER NOTCH
24	.0204"	.0316"	.0046"	CORNER NOTCH
25	.0198"	.0307"	.0045"	CORNER NOTCH
26	.0202"	.0314"	.0050"	CORNER NOTCH
27	.0205"	.0303"	.0044"	CORNER NOTCH
28	.0209"	.0312"	.0047"	CORNER NOTCH
29	.0202"	.0324"	.0045"	CORNER NOTCH
30	.0200"	.0317"	.0048"	CORNER NOTCH
31	.0201"	.0306"	.0047"	CORNER NOTCH
32	.0208"	.0319"	.0044"	CORNER NOTCH
33	.0206"	.0309"	.0048"	CORNER NOTCH

* SEE ATTACHED NOTE

NOTE: SEE ATTACHED CUSTOMER DRAWING FOR NOTCH REQUIREMENTS AND LOCATION.

FABRICATED BY: S. CHAMBERLAIN

APPROVED BY: Mitchell A. Dahl

ALL DIMENSIONS ARE MEASURED WITH DIMENSIONAL EQUIPMENT WHICH IS CERTIFIED AND TRACEABLE TO **NIST (#708) #5084918** AND **NIST (#783183) #5830553**. NUCLEAR REGULATORY COMMISSION RULES AND REGULATIONS 10 CFR PART 21 APPLIES TO THIS ORDER. ALL NOTCHES MANUFACTURED PER WESTPRO PROCEDURE WQC-IV.

NORTHRUP GRUMMAN IT PO#7500109901 ALUMINUM SPECTRA SPECIMENS 1-33

FROM

WESTPRO
3460 BRADY COURT, N.E.
SALEM, OR 97303
PH. (503) 585-6263 • FAX (503) 585-6577

QUICK MEMO

DATE: 12-4-12

ATTENTION: Robert Fidnarick

TO

NORTHRUP GRUMMAN IT

SUBJECT PO# 7500109901
Plate specimen #10
2024 T351 Aluminum

MESSAGE

Please note:

Notch in the ~~.125~~ .156 (R7) " Ø hole is off center of the 12 0 Clock location but notch dimensions are within the tolerance of Dwg# GT270KB003

NOTE (1) COUPON ID EDM NOTCH IS .025 INCHES BELOW THE .156 INCH DIAMETER HOLE CENTERLINE.

DISPOSITION: HOLD COUPON FOR FINAL SPARE OR USE AS TEST SETUP FOR SPECTRUM PROVE OUT

R7

SIGNED [signature] EDM DEPT.

Material: 2024T351 (.500 plate)
Heat number: 418964A3
Drawing No: GT270KB003-11
Coupon ID 1-33

A-10 TRAINING vs NON TRAINING MISSION COUPON MEASUREMENTS

Coupon ID	Thickness in	Width in	Hole dia in
1	0.410	4.000	0.156
2	0.409	4.000	0.156
3	0.410	4.001	0.156
4	0.410	4.001	0.156
5	0.410	4.001	0.156
6	0.410	4.000	0.156
7	0.410	4.001	0.156
8	0.410	4.001	0.156
9	0.410	3.999	0.156
10 (1)	0.410	4.000	0.156
11	0.410	4.000	0.156
12	0.410	4.000	0.156
13	0.412	4.000	0.156
14	0.409	3.999	0.156
15	0.410	4.000	0.156
16	0.410	3.999	0.156
17	0.409	4.000	0.156

Coupon ID	Thickness in	Width in	Hole dia in
18	0.410	4.000	0.156
19	0.411	4.000	0.156
20	0.410	3.999	0.157
21	0.411	4.000	0.156
22	0.410	4.000	0.155
23	0.411	4.000	0.156
24	0.411	4.000	0.156
25	0.409	4.000	0.156
26	0.410	4.000	0.156
27	0.410	4.000	0.156
28	0.409	4.000	0.156
29	0.410	3.990	0.156
30	0.410	4.000	0.156
31	0.410	4.000	0.156
32	0.409	4.000	0.156
33	0.410	4.000	0.156

Note: (1) Coupon 10 EDM notch was inadvertently machined .025 inches below the centerline.

APPENDIX B

FATIGUE MACHINE AND LOAD CELL CALIBRATION CERTIFICATIONS

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : 26-Oct-2010   CERTIFICATE NUMBER : 91102610134148

NVLAP

Lab code: 200301-0

INSTRON

Instron
825 University Avenue
Norwood, MA 02062-2643
Telephone: (800) 473 - 7838
Fax: (781) 575 - 5755
Email: service_requests@instron.com

APPROVED SIGNATORY

John L Paul

Digitally signed by John Paul
DN: cn=John Paul, o=GeoTrust True Credentials Customer - Organization not validated., ou=CPS terms incorporated by reference liability limited., See True Credentials Express CPS www.geotrust.com/resources/CPS., Email control validated by GeoTrust, Identity authenticated by Registration Authority (RA)., Registration Authority (RA) - Calibration_lab@instron.com, email=John_Paul@instron.com
document

Type of Calibration: speed
Relevant Standard: speed
Date of Calibration: 26-Oct-2010

Customer Requested Due Date: 26-Oct-2011

Customer		**Machine**	
	U S Air Force Hill AFB 00 ACL/MADLM 7278 4TH ST Layton, UT 84056	Serial No :	CJ3037
		Make :	Instron
		Model :	8800R
P.O. Number :		Ambient Temperature :	73.9 °F
Contact :	Cody Hone		

Readout Verified

1. Digital Readout (in/min)

Resolution of Indicator: .0001 in/min

Certification Statement

This certifies that the speeds verified with machine indicator 1 (listed above) were verified by Instron in accordance with Instron work instruction ICA-8-07.

The acceptable field calibration tolerance for certification is ± 0.5% of reading for Instron machines. For other machines, check the manufacturers specifications.

Method of Verification

The testing machine was verified on-site at customer location. The testing machine was verified in the 'as found' condition with no adjustments carried out, unless otherwise noted in the comments section of this certificate.

The verification and equipment used conform to a controlled Quality Assurance program which meets the specifications outlined in ANSI/NCSL Z540-1, ISO 10012, ISO 9001:2000, and ISO/IEC 17025:2005. The Instron measurement equipment used for verification is traceable to NIST.

The results indicated on this certificate and report relate only to the items verified. If there are methods or data included that are not covered by the NVLAP accreditation it will be identified in the comments. Any limitations of use as a result of this verification will be indicated in the comments. This report must not be used to claim product endorsement by NVLAP or the United States government. This report shall not be reproduced, except in full, without the approval of Instron.

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : **26-Oct-2010** CERTIFICATE NUMBER : **91102610134148**

Datapoint Summary - Indicator 1 - Digital Readout(in/min)

Indicated Speed (in/min)	Run1 Error(%)	Run2 Error(%)	Run3 Error(%)	Repeat Error (%)	Uncertainty (in/min)*	Coverage Factor = k
1	.525	.546	.731	.206	.00209	2
.25	.340	.682	.869	.529	.00088	2.45
.1	.784	.850	.839	.066	.00017	2

**The reported expanded uncertainty of measurement is based on a combined uncertainty multipied by a coverage factor k to provide a level of confidence of approximately 95 %.*

Data - Indicator 1 - Digital Readout(in/min)

Temperature at start of verification : 73.9 °F

Indicated Speed	Run 1			Run 2			Run 3		
(in/min)	Disp. (in)	Time (min)	Actual Speed (in/min)	Disp. (in)	Time (min)	Actual Speed (in/min)	Disp. (in)	Time (min)	Actual Speed (in/min)
1	.3302	.33193	.994778	.3295	.33130	.994567	.3284	.33080	.992745
.25	.3223	1.29358	.249153	.3226	1.29920	.248307	.3171	1.27942	.247847
.1	.3645	3.67357	.099222	.3290	3.31797	.099157	.3816	3.84802	.099168

Temperature at end of verification : 74.1 °F

Direction of Displacement: Down

Verification Equipment

Make/Model	Serial No.	Description	Cal Agency	Uncertainty of Calibration	Resolution	Cal Date	Due Date
Boeckeler DDI	1041	Linear Gage	A.A.Jansson	.000139 in	.0001 in	8-May-08	8-Nov-10
EXTECH 445580	960503	Thermometer	SYPRIS	.5 °F	.1°F	19-Sep-10	19-Sep-12
---	5G658B1	Computer Clock	Instron Calibrati	10 ms	1 ms	19-Jul-10	19-Jul-12

The standards used for this verification are traceable to NIST

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : 26-Oct-2010 CERTIFICATE NUMBER : 91102610134148

Datapoint Summary - Indicator 1 - Digital Readout(in/min)

Indicated Speed (in/min)	Run1 Error(%)	Run2 Error(%)	Run3 Error(%)	Repeat Error (%)	Uncertainty (in/min)*	Coverage Factor = k
1	.525	.546	.731	.206	.00209	2
.25	.340	.682	.869	.529	.00088	2.45
.1	.784	.850	.839	.066	.00017	2

**The reported expanded uncertainty of measurement is based on a combined uncertainty multiplied by a coverage factor k to provide a level of confidence of approximately 95 %.*

Data - Indicator 1 - Digital Readout(in/min)

Temperature at start of verification : 73.9 °F

Indicated Speed (in/min)	Run 1 Disp. (in)	Run 1 Time (min)	Run 1 Actual Speed (in/min)	Run 2 Disp. (in)	Run 2 Time (min)	Run 2 Actual Speed (in/min)	Run 3 Disp. (in)	Run 3 Time (min)	Run 3 Actual Speed (in/min)
1	.3302	.33193	.994778	.3295	.33130	.994567	.3284	.33080	.992745
.25	.3223	1.29358	.249153	.3226	1.29920	.248307	.3171	1.27942	.247847
.1	.3645	3.67357	.099222	.3290	3.31797	.099157	.3816	3.84802	.099168

Temperature at end of verification : 74.1 °F

Direction of Displacement: Down

Verification Equipment

Make/Model	Serial No.	Description	Cal Agency	Uncertainty of Calibration	Resolution	Cal Date	Due Date
Boeckeler DDI	1041	Linear Gage	A.A.Jansson	.000139 in	.0001 in	8-May-08	8-Nov-10
EXTECH 445580	960503	Thermometer	SYPRIS	.5 °F	.1°F	19-Sep-10	19-Sep-12
---	5G658B1	Computer Clock	Instron Calibrati	10 ms	1 ms	19-Jul-10	19-Jul-12

The standards used for this verification are traceable to NIST.

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : **26-Oct-2010** CERTIFICATE NUMBER : **91102610134148**

Comments

Verified By: John Paul
Service Engineer

CERTIFICATE OF CALIBRATION

ISSUED BY: INSTRON CALIBRATION LABORATORY

DATE OF ISSUE: 27-Oct-10 CERTIFICATE NUMBER: **91102710100102**

NVLAP

Lab code: 200301-0

INSTRON

Instron
825 University Avenue
Norwood, MA 02062-2643
Telephone: (800) 473-7838
Fax: (781) 575-5750
Email: service_requests@instron.com

APPROVED SIGNATORY

John L Paul

Digitally signed by John Paul
DN: cn=John Paul, o=GeoTrust True Credentials Customer - Organization not validated, ou=CPS terms incorporated by reference liability limited., See True Credentials Express CPS www.geotrust.com/resources/CPS., Email control validated by GeoTrust., Identity authenticated by Registration Authority (RA)., Registration Authority (RA) - Calibration_lab@instron.com, email=John_Paul@instron.com
Reason: I attest to the accuracy and integrity of this document

Type of Calibration: **Strain**
Relevant Standard: **ASTM E83 - 10**
Date of Calibration: **27-Oct-10**

Customer Requested Due Date: 27-Oct-11

Customer

Name:	U S Air Force Hill Air Force Base
Address:	00 ACL/MADLM 7278 4th St Layton UT 84056 WELDON.BETTS@HILL.AF.MIL
P.O./Contract No.:	
Contact:	Weldon Betts

Machine

Manufacturer:	Instron
Serial Number:	8800RCJ3037
System ID:	8800RCJ3037
Range Type:	Single

Transducer

Manufacturer:	Interlaken
Transducer ID:	3541-01/889078
Extensometer Type:	Type 2
Travel (Tension):	0.1 in
Gauge Length:	0.2 in
Mode:	Static (Tension)

Classification

The following indicators of the extensometer system were verified and classed:

Indicator Type	Description	Indicator Units	Range Full Scale (%)	System Class
1. GPIB		in	100	B-1

Certification Statement

All indicators listed above were verified on-site at customer location by Instron in accordance with ASTM E83.

The verification and equipment used conform to a controlled Quality Assurance program which meets the specifications outlined in ANSI/NCSL Z540-1, ISO 10012, ISO 9001:2000 and ISO/IEC 17025:2005.

The testing machine was verified in the 'as found' condition.

Instron Calpro Version 3.13

The results indicated on this certificate and the following report relate only to the items verified. If there are methods or data included that are not covered by the NVLAP accreditation it will be identified in the comments. Any limitations of use as a result of this verification will be indicated in the comments. This report must not be used to claim product endorsement by NVLAP or the United States government. This report shall not be reproduced, except in full, without the approval of the issuing laboratory.

CERTIFICATE OF CALIBRATION

NVLAP ACCREDITED CALIBRATION LABORATORY No. 200301-0

CERTIFICATE NUMBER:
91102710100102

Summary of Results

Indicator 1. - GPIB (in)

Range Full Scale (%)	Tested Range (in)	Mode	System Class*	Resolution (in)	Resolution Class	ASTM E83 Lower Limit (in)
100	0.01 to 0.1	Tension	B-1	0.0000005	A	0.00005

** System Class for a range is the worst of the following classes: resolution class, individual point error class, repeatability class and is also based on the measurement capability of the laboratory.*

Data Summary and Classification

Indicator 1. - GPIB (in)

% of Range	Run 1 Error Fixed (in)	Run 1 Error Relative (% of strain)	Run 2 Error Fixed (in)	Run 2 Error Relative (% of strain)	Repeat Error (in)	Worst Class	Uncertainty of Measurement* (in)
100% Range (Full Scale: 0.1 in)							
10	0.00005	0.481	0.00005	0.493	0.00000	B-1	0.000102
20	0.00001	0.043	0.00003	0.135	0.00002	B-1	0.000102
40	0.00015	0.369	0.00017	0.418	0.00002	B-1	0.000102
70	0.00010	0.138	0.00015	0.211	0.00005	B-1	0.000102
100	-0.00002	-0.019	0.00002	0.022	0.00004	A	0.000102

** The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95%.*

Data

Indicator 1. - GPIB (in)

% of Range	Run 1 Indicated (in)	Run 1 Applied (in)	Run 2 Indicated (in)	Run 2 Applied (in)
100% Range (Full Scale: 0.1 in)	Run Temperature: 73.0 °F		Run Temperature: 73.0 °F	
0	-0.0000012	0.000000	0.0000167	0.000000
10	0.0100469	0.010000	0.0100660	0.010000
20	0.0200073	0.020000	0.0200436	0.020000
40	0.0401462	0.040000	0.0401837	0.040000
70	0.0700951	0.070000	0.0701644	0.070000
100	0.0999797	0.100000	0.1000390	0.100000

Verification Equipment and Usage

Verification Equipment:

Make/Model	Serial Number	Description	Calibration Agency	Measurement Range	Cal Date	Cal Due
Extech 445580	960503	temp. indicator	Sypris	NA	19-Aug-10	19-Aug-12

Instron Calpro Version 3.13

CERTIFICATE OF CALIBRATION

NVLAP ACCREDITED CALIBRATION LABORATORY No. 200301-0

CERTIFICATE NUMBER:
91102710100102

Verification Equipment:

Make/Model	Serial Number	Description	Calibration Agency	Measurement Range	Cal Date	Cal Due
Boeckeler Micrometer 1338	32746	disp. indicator	A.A. Jansson	1.00 in	30-Oct-09	30-Oct-10

Verification Equipment Usage:

Measurement Type	Serial Number	Range (% Full Scale)	Percent(s) of Range
Displacement	32746	100	0/10/20/40/70/100

Instron standards are traceable to NIST and/or other National standards.

Comments

Verified by: John Paul
Field Service Engineer

NOTE: Clause 9 of ASTM E-83: 2006 states; It is recommended that extensometer systems be verified annually or more frequently if required. In no case shall the time interval between verifications exceed 18 months (unless an extensometer is being used in a long-time test running beyond the 18 month period). An extensometer system shall not be used after an adjustment or repair that could affect its accuracy without first verifying its accuracy utilizing the procedure described in this practice.

CERTIFICATE OF CALIBRATION

NVLAP

Lab code: 200301-0

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : **26-Oct-2010** CERTIFICATE NUMBER: **91102610125508**

INSTRON

Instron
825 University Avenue
Norwood, MA 02062-2643
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APPROVED SIGNATORY

John L Paul

Digitally signed by John Paul
DN: cn=John Paul, o=GeoTrust True Credentials Customer - Organization not validated., ou=CPS terms incorporated by reference liability limited., See True Credentials Express CPS www.geotrust.com/resources/CPS., Email control validated by GeoTrust., Identity authenticated by Registration Authority (RA)., Registration Authority (RA) - Calibration_lab@instron.com, email=John_Paul@instron.com
Reason: I attest to the accuracy and integrity of this document

Type of Calibration: linear
Relevant Standard: linear
Date of Calibration: 26-Oct-2010 **Customer Requested Due Date: 26-Oct-2011**

Customer	U S Air Force Hill AFB 00 ACL/MADLM 7278 4TH ST Layton, UT 84056
P.O. Number :	
Contact :	Cody Hone

Machine	
Serial No :	CJ3037
Make :	Instron
Model :	8800R
Ambient Temperature :	74.1 °F

Readout Verified

1. Digital Readout (in)

Certification Statement

This certifies that the displacements verified with machine indicator 1 (listed above) were verified by Instron in accordance with Instron work instruction ICA-8-07.

The acceptable field calibration tolerance for certification is ± 1.0% full travel for Instron machines. For other machines, check the manufacturers specifications.

Method of Verification

The testing machine was verified on-site at customer location. The testing machine was verified in the 'as found' condition with no adjustments carried out, unless otherwise noted in the comments section of this certificate.

The verification and equipment used conform to a controlled Quality Assurance program which meets the specifications outlined in ANSI/NCSL Z540-1, ISO 10012, ISO 9001:2000, and ISO/IEC 17025:2005. The Instron measurement equipment used for verification is traceable to NIST.

The results indicated on this certificate and report relate only to the items verified. If there are methods or data included that are not covered by the NVLAP accreditation it will be identified in the comments. Any limitations of use as a result of this verification will be indicated in the comments. This report must not be used to claim product endorsement by NVLAP or the United States government. This report shall not be reproduced, except in full, without the approval of Instron.

CalproSDS version 3.3

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : 26-Oct-2010 CERTIFICATE NUMBER: 91102610125508

Summary of Results

Tested Displacement Ranges(in)	Max Error (% FS)	Direction	Max Repeat Error (% FS)	Max Uncertainty(in)	Resolution (in)
0.60 - 3.00	0.46	Tension	0.008	0.0010	.0001
0.60 - 3.00	-1.00	Compression	0.030	0.0028	.0001

Datapoint Summary - Indicator 1 - Digital Readout(in)

Tension

Sugg Value	Run1 Error (% FS)	Run2 Error (% FS)	Run3 Error (% FS)	Repeat Error (% FS)	Uncertainty (in)*	Coverage Factor = k
0.6	-.037	-.037	-.038	.001	.0007	2.26
1.2	.130	.133	.138	.008	.0009	2.26
1.8	.342	.347	.347	.005	.0008	2.26
2.4	.455	.463	.462	.008	.0010	2.26
3	.427	.425	.430	.005	.0009	2.26

Compression

Sugg Value	Run1 Error (% FS)	Run2 Error (% FS)	Run3 Error (% FS)	Repeat Error (% FS)	Uncertainty (in)*	Coverage Factor = k
0.6	-.373	-.343	-.345	.030	.0028	3.18
1.2	-.750	-.762	-.762	.012	.0011	2.36
1.8	-.977	-.985	-.997	.020	.0017	2.78
2.4	-.945	-.945	-.950	.005	.0009	2.26
3	-.743	-.748	-.747	.005	.0009	2.26

**The reported expanded uncertainty of measurement is based on a combined uncertainty multipied by a coverage factor k to provide a level of confidence of approximately 95 %.*

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : **26-Oct-2010** CERTIFICATE NUMBER: **91102610125508**

Data - Indicator 1 - Digital Readout(in)

Temperature at start of verification : 74.1 °F

Tension

Sugg Value	Run 1 Applied	Run 1 Indicated	Run 2 Applied	Run 2 Indicated	Run 3 Applied	Run 3 Indicated
0.6	.6022	.6	.6022	.6	.6023	.6
1.2	1.1922	1.2	1.1920	1.2	1.1917	1.2
1.8	1.7795	1.8	1.7792	1.8	1.7792	1.8
2.4	2.3727	2.4	2.3722	2.4	2.3723	2.4
3	2.9744	3	2.9745	3	2.9742	3

Compression

Sugg Value	Run 1 Applied	Run 1 Indicated	Run 2 Applied	Run 2 Indicated	Run 3 Applied	Run 3 Indicated
0.6	.6224	.6	.6206	.6	.6207	.6
1.2	1.2450	1.2	1.2457	1.2	1.2457	1.2
1.8	1.8586	1.8	1.8591	1.8	1.8598	1.8
2.4	2.4567	2.4	2.4567	2.4	2.4570	2.4
3	3.0446	3	3.0449	3	3.0448	3

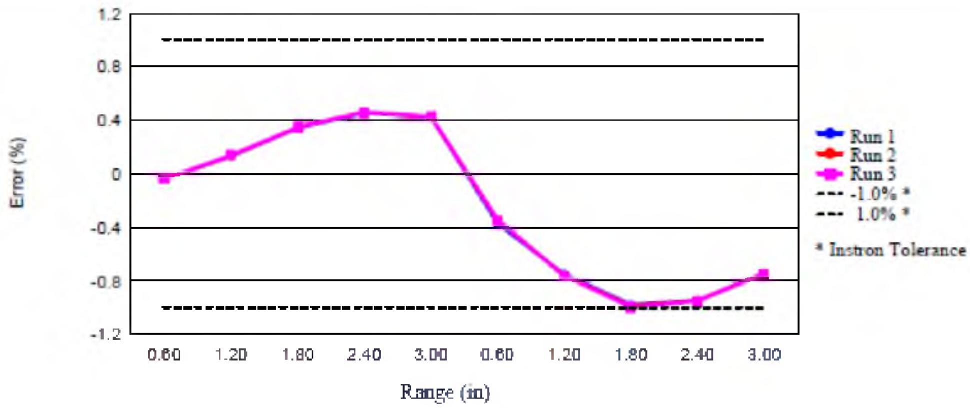
Temperature at end of verification : 73.9 °F

CERTIFICATE OF CALIBRATION

ISSUED BY : INSTRON CALIBRATION LABORATORY

DATE OF ISSUE : 26-Oct-2010 CERTIFICATE NUMBER: 91102610125508

Graphical Data - Indicator 1 -Digital Readout (in)



Verification Equipment

Make/Model	Serial No.	Description	Cal Agency	Uncertainty of Calibration	Resolution	Cal Date	Due Date
Boeckeler DDI	1041	Linear Gage	A.A.Jansson	.000139 in	.0001 in	8-May-08	8-Nov-10
EXTECH 445580	960503	Thermometer	SYPRIS	.5 °F	.1 °F	19-Sep-10	19-Sep-12

The standards used for this verification are traceable to NIST.

Comments

Verified By: John Paul
Service Engineer

CalproSDS version 3.3

APPENDIX C

NEWMAN RAJU STRESS INTENSITY EQUATION

MAIN EQUATIONS FOR CALCULATING THE STRESS INTENSITY IN A SINGLE CORNER CRACK OF A HOLE

$$K_{one\ crack} = \sqrt{\left(\frac{4}{\pi} + \frac{ac}{2tr}\right) \Big/ \left(\frac{4}{\pi} + \frac{ac}{tr}\right)}\, K_{two\ cracks}$$

$$K_{two\ cracks} = (St + H_{ch}S_b)\sqrt{\pi\frac{a}{Q}}\, F_{ch}\left(\frac{a}{c}, \frac{a}{t}, \frac{r}{t}, \frac{r}{b}, \frac{c}{b}, \frac{c}{b}, \phi\right)$$

for $0.2 < {}^{a}/_{c} < 2, {}^{a}/_{t} < 1, 0.5 < {}^{r}/_{t} < 2, {}^{(r+c)}/_{b} < 0.5$, and $0 < \phi < {}^{\pi}/_{2}$

$$F_{ch} = \left[M_1 + M_2\left(\frac{a}{t}\right)^2 + M_3\left(\frac{a}{t}\right)^4\right] g_1 g_2 g_3 g_4 f_\phi f_w$$

for ${}^{a}/_{c} < 1$: $M_1 = 1.13 - 0.09({}^{a}/_{c})$, $M_2 = -0.54 + 0.89/(0.2 + {}^{a}/_{c})$,

$$M_3 = 0.5 - 1/(0.65 + {}^{a}/_{c}) + 14(1 - {}^{a}/_{c})^{24},$$

$$g_1 = 1 + \left[0.1 + 0.35({}^{a}/_{t})^2\right](1 - \sin\phi)^2,$$

$$g_2 = \frac{1 + 0.358\lambda + 1.425\lambda^2 - 1.578\lambda^3 + 2.156\lambda^4}{1 + 0.13\lambda^2},$$

where $\lambda = 1/(1 + {}^{c}/_{r}\cos(\mu\phi))$,

$$g_3 = (1 + 0.04\,{}^{a}/_{c})[1 + 0.1(1 - \cos\phi)^2][0.85 + .15({}^{a}/_{c})^{1/4}],$$

$$g_4 = 1 - 0.7(1 - {}^{a}/_{t})({}^{a}/_{c} - 0.2)(1 - {}^{a}/_{c}),\ f_\phi = [({}^{a}/_{c})^2(\cos\phi)^2 + (\sin\phi)^2]^{1/4}$$

$$f_w = \left\{\sec\left(\frac{\pi r}{2b}\right)\sec\left[\frac{\pi(2r + nc)}{4(b - c) + 2nc}\sqrt{\frac{a}{t}}\right]\right\}^{1/2}$$

APPENDIX D

PROCEDURES FOR AFGROW ANALYSIS

STEP BY STEP PROCESS TO USE AFGROW BASED ON THE GUIDELINES PREPARED BY THE UNITED STATES AIR FORCE

1. Create Title: Brief description of model.
2. Select Material: This analysis used a file containing material properties and parameters for the Forman equation to simulate the 2024-T351 Aluminum Alloy in the AFGROW program. The information in the file is a general guide and some material properties may need to be adjusted based on manufacturing thicknesses or other factors. Reference the Metallic Materials Properties Development and Standardization (MMPDS) to verify correct material properties.
3. Create Model: From a selection of “Classic Models”, choose the appropriate geometric model. For this analysis, the “Single Corner Crack at Hole” model was chosen.

a. Enter problem geometric factors including: thickness, width, hole diameter, initial flaw size (IFS), offset, etc.

i. Check: keep A/C constant

ii. Uncheck: Oblique through crack

iii. IFS: Unless otherwise specified, the initial flaw size should be the same in both the “A” and “C” directions. For this analysis an average of the precrack sizes, for each type of test conducted, were used.

b. Select Load Type: Ratio of tension or bearing stress to reference stress must be input for each load case (tension stress fraction = 1.0 if bearing stress is zero). The test for this analysis was purely tensile.

4. Open Spectrum File: For this analysis the A and B spectrum files, specifically created to be used in AFGROW, were utilized. AFGROW require that the files be normalized with the greatest value given a value of 1.0 and all other loads be represented as a fraction of the highest load.

a. Stress Multiplication Factor (SMF): Enter the max stress of the spectrum. Since the values in the spectrum files are representative of loads the SMF had to include a conversion factor to make the values in the spectrum files convert to stresses.

5. Select a Retardation Model: For this analysis several retardation models were attempted to obtain the best fit to the test data.
6. Predict Function Preferences: Used for establishing various analysis criteria and outputs.

a. Select Growth Increments: Cycle by Cycle Beta and Spectrum calculation. Use a Max Growth Increment of 0.25%

b. Enter Output Intervals: Specify crack growth increments. Increment = 0.01”

c. Enter Number of Hours per Pass: Conversion factor for calculating effective flight hours (EFH) from segment count.

d. Select Output Options: Typically the user will select the data file and plot file options for crack growth data.

e. Select Propagation Limits: Unless otherwise specified use the Kmax and the Net Section Section Yield failure criteria.

f. If using Forman, as was done for this analysis, select User-Defined Kmax and enter an appropriate value for the material.

g. Enter Transition to Through Crack: Use default unless otherwise specified.

7. Select Stress State: Use default unless otherwise specified.
8. Select Beta Criteria: Use AFGROW standard solution betas for standard geometries.
9. At this point the user is ready to run the analysis.

APPENDIX E

CRACK GROWTH DATA SHEETS

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-1
Width: ___4.00 in_______ Thick:__.410 in_________ Area: 1.64 in^2

Precrack Information

Precrack Date: May 31, 2013____ Loading Condition: Constant Amplitude R=.05_____
Frequency:_7 hz___________ Hole Diameter:0.156 in_ Peak Stress:_19.5 ksi____
Surface EDM Length: 0.0301 in Bore EDM Length: 0.0044 in

Testing Information

Test Date: March 3, 2014 Loading Condition:_Variable Amplitude_
Constant Load Rate:100 kip/sec Spectrum:__Baseline Spectrum A
____
Surface EDM Length:_.042 in Hole Diameter:_.250 in
Peak Stress:__27.9 ksi___________

EFH	Crack Length (inches)				
	EDM Side			Opposite Side	
	Front	Back	Bore	Front	Back
0	0.047		0.097		
3257.108	0.061		0.12		
4885.662	0.074		0.149		
6514.216	0.086		0.149		
8142.77	0.103		0.166		
9119.902	0.123		0.181		
9771.324	0.124		0.185		
10422.75	0.125		0.192		
11074.17	0.134		0.202		
11725.59	0.143		0.213		
12377.01	0.152		0.226		
13028.43	0.163		0.233		
13679.85	0.173		0.244		
14331.28	0.183		0.249		
14982.7	0.196		0.267		
15634.12	0.206		0.282		
16285.54	0.223		0.2915		
16936.96	0.234		0.301		

17588.38	0.249		0.314		
18239.8	0.267		0.339		
18565.52	0.271		0.35		
18891.23	0.282		0.357		
19216.94	0.288		0.363		
19542.65	0.294		0.3745		
19868.36	0.302		0.383		
20194.07	0.311	0.002			
20356.92	0.314	0.026			
20682.64	0.321	0.066			
21008.35	0.33	0.1085			
21334.06	0.348	0.152			
21496.91	0.349	0.1665			
21822.62	0.355	0.1955			
22148.33	0.359	0.223			
22474.04	0.372	0.2455			
22799.76	0.381	0.2645			
23125.47	0.395	0.284			
23451.18	0.406	0.299			
23776.89	0.415	0.318			
24102.6	0.429	0.3345			
24428.31	0.441	0.3565			
24754.02	0.457	0.373			
25079.73	0.472	0.392			
25405.44	0.609	0.537			
25731.15	0.623	0.5565		0.024	
26056.86	0.629	0.577		0.038	
26382.57	0.654	0.5965		0.047	
26708.29	0.667	0.616		0.056	
27034	0.688	0.645		0.074	0.04
27359.71	0.713	0.664		0.091	0.062
27685.42	0.733	0.693		0.104	0.083
28011.13	0.751	0.716		0.127	0.103
28336.84	0.78	0.743		0.148	0.124
28662.55	0.804	0.78		0.173	0.153
28988.26	0.837	0.814		0.206	0.2
29313.97	0.872	0.855		0.243	0.233
29476.83	0.888	0.879		0.259	0.25
29639.68	0.905	0.898		0.28	0.271

29802.54	0.927	0.917		0.299	0.295
29965.39	0.963	0.945		0.325	0.327
30128.25	0.979	0.9695		0.339	0.35
30291.1	1.015	1.008		0.372	0.383
30453.96	1.09	1.082		0.425	0.44
30551.67	1.111	1.117		0.465	0.4
Final Specimen Fracture					

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-2
Width: ___4.00 in_______ Thick: _.409 in_________ Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 3, 2013 Loading Condition: Constant Amplitude R=.05_____
Frequency: 7 hz___________ Hole Diameter: 0.156 in Peak Stress: 19.5 ksi____
Surface EDM Length: 0.0310 in Bore EDM Length: 0.0046 in

Testing Information

Test Date: N/A_____ Loading Condition: _N/A_
Constant Load Rate: N/A___ Spectrum: __N/A___________________
Surface EDM Length: _N/A Hole Diameter N/A
Peak Stress: __N/A___________

This sample exceeded the precrack final size criteria and was removed from the test matrix and used as for load frame calibration.

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-3
Width: ___4.00 in_______ Thick: _.409 in_________ Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 4, 2013 Loading Condition: Constant Amplitude R=.05_____
Frequency: 7 hz___________ Hole Diameter: 0.156 in Peak Stress: 19.5 ksi____
Surface EDM Length: 0.0307 in Bore EDM Length: 0.0046 in

Testing Information

Test Date: Feb 24, 2014 Loading Condition: _Variable Amplitude_
Constant Load Rate: 100 Kips/sec Spectrum: __Spectrum A+B Combination
Surface EDM Length: _0.0465 in Hole Diameter .253 in
Peak Stress: __27.9 Ksi________

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.0465		0.0613			
2550	0.06642		0.1013			
4916	0.08368		0.1385			
7595	0.10264		0.1665			
10441	0.13682		0.2008			Switch to B
63456	0.14446		0.2065			
108481	0.1887		0.2228			
142068	0.21598		0.2526			
161545	0.24468		0.3140			

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-4
Width: ___4.00 in_______ Thick: _.410 in________ Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 5, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0306 in Bore EDM Length: 0.0047 in

Testing Information

Test Date: Aug 01, 2013 Loading Condition: Variable Amplitude
Constant Load Rate: 100 Kips/sec Spectrum: Baseline Spectrum A
Surface EDM Length: 0.04504 in Hole Diameter .255 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)				
	EDM Side			Opposite Side	
	Front	Back	Bore	Front	Back
0	0.04504		0.0826		
113	0.04632		0.0847		
168	0.04856		0.0847		
274	0.04864		0.09314		
299	0.04864		0.095878		
334	0.05108		0.095878		
399	0.05286		0.098468		
532	0.05412		0.100614		
595	0.05412		0.102908		

709	0.05752		0.1082		
1639	0.06178		0.115638		
2349	0.06818		0.120041		
3340	0.07958		0.13451		
4056	0.08698		0.145389		
4450	0.09416		0.146869		
5073	0.10376		0.156527		
6112	0.11146		0.176176		
7403	0.12428		0.188425		
8257	0.14378		0.200932		
8589	0.14656		0.207963		
9115	0.16172		0.211927		
9739	0.17546		0.219915		
10566	0.19384		0.227945		
11474	0.2093		0.255217		
12174	0.2242		0.282193		
13218	0.25536		0.313905		
13704	0.27198		0.335997		
14364	0.29264		0.356164		
14922	0.30938		0.41056		
15308	0.32116			0.42842	0.13376
15482	0.33384			0.4411	0.16326
15667	0.33492			0.44218	0.2016
15856	0.34042			0.44768	0.22066
16301	0.36074			0.468	0.2714
16733	0.37378			0.48104	0.3094
17075	0.38422			0.49148	0.33738
17471	0.4083			0.51556	0.36192
17925	0.42572			0.53298	0.39708
18305	0.44692			0.55418	0.43438
18985	0.48256			0.58982	0.4724
19865	0.53636			0.64362	0.54432
20354	0.57386			0.68112	0.59376
20630	0.59994			0.7072	0.62574
21003	0.63684			0.7441	0.67202
21461	0.69024			0.7975	0.72912
21918	0.75092			0.85818	0.79342
22210	0.79748			0.90474	0.84936

22355	0.81952			0.92678	0.8745
22526	0.87478			0.98204	0.92992
22698	0.91818			1.02544	0.98136
22855	0.96624			1.0735	1.0192
22996	1.01956			1.12682	1.08222
23079	1.07238			1.17964	1.15046
23136	1.18318			1.29044	1.2613

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-5
Width: ___4.00 in_______ Thick: _.410 in_________ Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 5, 2013 Loading Condition: Constant Amplitude R=.05_____
Frequency: _7 hz___________ Hole Diameter: 0.156 in Peak Stress: _19.5 ksi____
Surface EDM Length: 0.0309 in Bore EDM Length: 0.0046 in

Testing Information

Test Date: Feb 14, 2014 Loading Condition: _Variable Amplitude_
Constant Load Rate: 200 Kips/sec Spectrum: __Baseline Spectrum A
Surface EDM Length: _0.0353 in Hole Diameter .254 in
Peak Stress: __27.9 Ksi________

EFH	Crack Length (inches)				
	EDM Side			Opposite Side	
	Front	Back	Bore	Front	Back
0	0.03534		0.1016		
169	0.035		0.1016		
1833	0.0512		0.1251		
2811	0.06822		0.1433		
5107	0.07044		0.1433		
6451	0.0871		0.1433		
9086	0.11822		0.1855		
11995	0.14892		0.2291		
15182	0.198		0.2595		
18187	0.26122		0.3344		
20949	0.3326	0.14084			
22501	0.38306	0.26108			
25882	0.50552	0.4532			
27459	0.60744	0.56146			
28382	0.680006				
30519	0.92902				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-6
Width: ___4.00 in_______ Thick:_.410 in_________ Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 7, 2013 Loading Condition: Constant Amplitude R=.05_____
Frequency:_7 hz____________ Hole Diameter:0.156 in Peak Stress:_19.5 ksi____
Surface EDM Length: 0.0313 in Bore EDM Length: 0.0045 in

Testing Information

Test Date: Sept 3, 2013 Loading Condition:_Variable Amplitude_
Constant Load Rate:150 Kips/sec Spectrum:__Spectrum A+B Combo 1
Surface EDM Length:_0.055 in Hole Diameter .250 in
Peak Stress:__27.9 Ksi________

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.055		0.138819			
984	0.08608		0.152384			
2301	0.09748		0.177			
3010	0.10728		0.185932			
4027	0.11978		0.194461			
4409	0.12488		0.198522			Switch to B
36588	0.12488		0.1985			
45735	0.12488		0.1985			
57169	0.12488		0.1985			
73545	0.1596		0.211397			
83467	0.1596		0.211397			
90602	0.16788		0.224617			
97195	0.1751		0.231298			
104456	0.17956		0.241451			

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-7
Width: ____4.00 in________ Thick: _.410 in__________ Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 7, 2013 ______ Loading Condition: Constant Amplitude R=.05______
Frequency: _7 hz____________ Hole Diameter: 0.156 in Peak Stress: _19.5 ksi_____
Surface EDM Length: 0.0310 in Bore EDM Length: 0.0044 in

Testing Information

Test Date: Feb 6, 2014 Loading Condition: _Variable Amplitude_
Constant Load Rate: 100 Kips/sec Spectrum: __ Spectrum A+B Combo 1
Surface EDM Length: _0.044 in Hole Diameter .251 in
Peak Stress: __27.9 Ksi_________

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.044		0.094			
163	0.049		0.099			
326	0.050		0.108			
489	0.050		0.109			
651	0.053		0.118			

977	0.056		0.126			
1629	0.058		0.13			
2280	0.062		0.132			
3257	0.068		0.161			
3583	0.069		0.169			
3909	0.072		0.173			
4234	0.080		0.173			
4560	0.084		0.175			
4886	0.085		0.177			
5211	0.086		0.179			
5537	0.087		0.179			
5863	0.089		0.179			
6514	0.092		0.179			
6840	0.095		0.179			
7166	0.100		0.179			
8143	0.108		0.179			
8794	0.116		0.186			
9120	0.121		0.192			
9169	0.121		0.2			Switch to B
45735	0.126		0.251			
91471	0.148		0.273			
109765	0.164		0.289			
118912	0.173		0.298			
128059	0.186		0.311			
137206	0.196		0.321			
146353	0.208		0.333			
155500	0.220		0.345			
164647	0.233		0.358			
173794	0.243		0.368			
182941	0.253		0.378			
192088	0.267		0.392			

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-8
Width: 4.00 in Thick: .410 in Area: 1.64 in^2
Precrack Information
Precrack Date: Jun 7, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi

Surface EDM Length: 0.0309 in   Bore EDM Length: 0.0048 in

Testing Information
Test Date: Feb 21, 2014   Loading Condition: Variable Amplitude
Constant Load Rate: 200 Kips/sec   Spectrum: Spectrum A+B Combo 2
Surface EDM Length: 0.028 in   Hole Diameter .253 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.0275		0.072			
3282	0.06074		0.111			
6180	0.07742		0.128			
9741	0.10948		0.193			
12951	0.1369		0.231			
15193	0.17308		0.271			
18223	0.21852		0.328			Switch to B
26913	0.21852		0.328			
66024	0.22854		0.373			
123931	0.29704		0.373			
164969	0.3622	0.269				
185701	0.41348	0.353				
211164	0.47238	0.408				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-9
Width: 4.00 in   Thick: .410 in   Area: 1.64 in^2

Precrack Information
Precrack Date: Jun 10, 2013   Loading Condition: Constant Amplitude
R=.05
Frequency: 7 hz   Hole Diameter: 0.156 in   Peak Stress: 19.5
ksi
Surface EDM Length: 0.0306 in   Bore EDM Length: 0.0045 in

Testing Information
Test Date: Mar 20, 2014   Loading Condition: Variable Amplitude
Constant Load Rate: 100 Kips/sec   Spectrum: Spectrum A+B Combo 3
Surface EDM Length: 0.0345 in   Hole Diameter .252 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)			Comments
	EDM Side	Opposite Side		

	Front	Back	Bore	Front	Back	
0	0.035		0.077			
3257	0.058		0.112			
4886	0.066		0.124			
6514	0.077		0.137			
8143	0.087		0.148			
9771	0.100		0.173			
11400	0.115		0.183			
13028	0.133		0.204			
14657	0.153		0.223			
16286	0.176		0.253			
17914	0.200		0.278			
19543	0.233		0.320			
20194	0.245		0.338			
20845	0.260		0.343			
21497	0.275		0.352			
22148	0.290		0.365			Switch to B
22832	0.304	0.008				
32015	0.310	0.023				
54882	0.313	0.039				
68603	0.319	0.056				
75746	0.326	0.100				
80037	0.330	0.139				
84610	0.335	0.173				
89184	0.343	0.218				
93757	0.347	0.252				
98331	0.356	0.284				
102904	0.363	0.294				
107478	0.374	0.316				
112051	0.384	0.334				
116625	0.396	0.350				
121198	0.405	0.359				
128059	0.422	0.378				
132632	0.433	0.392				
137206	0.445	0.409				
141779	0.456	0.426				
146353	0.469	0.433				
150926	0.482	0.453				
160073	0.509	0.474		0.09		

164647	0.520	0.490		0.1		
173794	0.556	0.516		0.108		
178367	0.562	0.529		0.112		
182941	0.580	0.540		0.0823		
187514	0.593	0.561		0.128		
192088	0.609	0.582		0.134		
196661	0.626	0.595		0.144		
201235	0.642	0.614		0.155		
205808	0.658	0.635		0.17		
210382	0.675	0.652		0.181		
214955	0.697	0.674		0.194	0.124	
219529	0.723	0.692		0.217	0.143	
224102	0.743	0.718		0.234	0.162	
228676	0.767	0.746		0.255	0.192	
233249	0.795	0.780		0.279	0.218	
237823	0.823	0.810		0.305	0.243	
242397	0.856	0.841		0.336	0.277	
246970	0.894	0.876		0.36	0.303	
251544	0.933	0.918		0.402	0.341	
256117	0.973	0.953		0.436	0.407	
260691	1.027	1.017		0.479	0.459	
265264	1.110	1.106		0.533	0.523	
269838	1.380	1.302		0.631	0.665	
270039	**Final Specimen Fracture**					

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-10
Width: 4.00 in Thick: .410 in Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 10, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0312 in Bore EDM Length: 0.0044 in

Testing Information

Test Date: Feb 14, 2014 Loading Condition: Variable Amplitude
Constant Load Rate: 100 Kips/sec Spectrum: Spectrum A+B Combo 2
Surface EDM Length: 0.0300 in Hole Diameter .251 in
Peak Stress: 27.9 Ksi

Coupon 10 EDM Notch was inadvertently machined .025 inches below the centerline.

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.030		0.087			
326	0.036		0.091			
651	0.040		0.093			
1303	0.047		0.093			
1954	0.049		0.093			
2606	0.052		0.103			
3257	0.057		0.109			
3909	0.061		0.109			
4886	0.064		0.109			
5537	0.069		0.121			
6189	0.074		0.129			
6840	0.081		0.137			
7491	0.088		0.141			
8143	0.092		0.151			
8794	0.098		0.151			
9771	0.112		0.161			
10423	0.118		0.171			
11074	0.125		0.176			
11726	0.134		0.174			
12377	0.140		0.184			
13028	0.150		0.200			
13680	0.157		0.204			
14331	0.168		0.214			
14983	0.175		0.222			
15634	0.188		0.232			
16286	0.200		0.250			
16611	0.203		0.285			
16937	0.208		0.292			
17100	0.211		0.297			
17426	0.216		0.305			
17751	0.222		0.321			
17849	0.223		0.329			Switch to B

40717	0.228		0.331			
63584	0.23		0.335			
104746	0.257		0.345			
123040	0.274		0.351			
132187	0.292		0.363			
136760	0.2985		0.365			
141334	0.309		0.371			
145907	0.32		0.385			
150481	0.32		0.391			
155055	0.332	0.007				
157341	0.333	0.138				
159628	0.337	0.173				
161915	0.341	0.191				
164202	0.348	0.211				
168775	0.354	0.238				
173349	0.361	0.251				
177922	0.369	0.269				
182496	0.375	0.279				
187069	0.385	0.29				
191643	0.394	0.305				
196216	0.405	0.331				
200790	0.412	0.337				
205363	0.42	0.351				
209937	0.432	0.366				
214510	0.441	0.38				
219084	0.454	0.392				
223657	0.463	0.402				
228231	0.475	0.42				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-11
Width: ___4.00 in_______ Thick: _.410 in_________ Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 10, 2013 Loading Condition: Constant Amplitude R=.05_____
Frequency: _7 hz___________ Hole Diameter: 0.156 in Peak Stress: _19.5 ksi____
Surface EDM Length: 0.0298 in Bore EDM Length: 0.0045 in

Testing Information

Test Date: Aug 21, 2013 Loading Condition: _Variable Amplitude_

Constant Load Rate:300 Kips/sec Spectrum:__ Spectrum A+B Combo 2
Surface EDM Length:_ 0.0500 in Hole Diameter .251 in
Peak Stress:__ 27.9 Ksi________

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.050		0.094			
240	0.059		0.119			
493	0.068		0.132			
1066	0.082		0.149			
1710	0.093		0.157			
2355	0.101		0.173			
3046	0.118		0.185			
3548	0.129		0.196			
4445	0.148		0.209			
5153	0.161		0.237			
5830	0.176		0.255			
6387	0.194		0.271			
6822	0.207		0.271			
7365	0.222		0.296			
7801	0.238		0.319			
8097	0.246		0.328			Switch to B
35016	0.260		0.334			
50130	0.288		0.357			
58647	0.307		0.370			
66675	0.317		0.405			
67260	0.322		0.413			
73788	0.331	0.190				
77615	0.338	0.236				
89727	0.366	0.298				
98641	0.379	0.340				
113300	0.424	0.397				
126478	0.468	0.447				
141295	0.516	0.495				
160558	0.585	0.586				
172814	0.627	0.636				
178358	0.659	0.658				
190517	0.698	0.714				
197275	0.730	0.754				

201005	0.757	0.781				
206970	0.787	0.805				
218074	0.823	0.835				
233025	0.860	0.870				
255857	0.906	0.942				
284172	0.961	0.994				
316499	0.997	1.040				
352517	1.064	1.089				
391018	1.092	1.126				
433269	1.154	1.140				
478418	1.228	1.225				
525310	1.330	1.327				
572410	**Final Specimen Fracture**					

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-12
Width: ___4.00 in_______ Thick:_.410 in_________ Area: 1.64 in^2

Precrack Information

Precrack Date: May 331, 2013 Loading Condition: Constant Amplitude R=.05_____
Frequency:_7 hz___________ Hole Diameter:0.156 in Peak Stress:_19.5 ksi____
Surface EDM Length: 0.0307 in Bore EDM Length: 0.0046 in

Testing Information

Test Date: Aug 21, 2013 Loading Condition:_Variable Amplitude_
Constant Load Rate:100 Kips/sec Spectrum:__ Spectrum A+B Combo 3
Surface EDM Length:_0.0467 in Hole Diameter .251 in
Peak Stress:__27.9 Ksi________

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.047		0.108			
578	0.063		0.121			
2544	0.085		0.151			
3977	0.101		0.168			
5898	0.121		0.197			
7790	0.158		0.233			
10069	0.202		0.296			
11781	0.239		0.304			
13327	0.271		0.348			
13792	0.292		0.355			
14221	0.304		0.381			
14322	0.304		0.400			
14387	0.304	0.005	0.410			Switch to B
23203	0.304	0.016				
27820	0.307	0.021				
44971	0.307	0.026				
61732	0.307	0.066				
90850	0.354	0.223				
117332	0.420	0.337				
130629	0.454	0.381				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-13
Width: 4.00 in Thick: .412 in Area: 1.65 in^2

Precrack Information

Precrack Date: Jun 12, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 7 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0307 in Bore EDM Length: 0.0046 in

Testing Information

Test Date: Sept 4, 2013 Loading Condition: Variable Amplitude
Constant Load Rate: 140 Kips/sec Spectrum: Spectrum A+B Combo 3
Surface EDM Length: 0.0458 in Hole Diameter .250 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.046		0.106			
1372	0.063		0.115			
2703	0.072		0.126			
4353	0.090		0.137			
6423	0.107		0.155			
9295	0.140		0.174			
11282	0.166		0.224			
14127	0.214		0.288			
15885	0.254		0.320			
17137	0.284		0.356			
18365	0.308		0.387			Switch to B
19521	0.335	0.080				
46905	0.343	0.110				
67041	0.353	0.154				
76910	0.356	0.190				
86981	0.371	0.233				
98141	0.404	0.281				
107895	0.421	0.317				
116967	0.450	0.343				
126350	0.470	0.384				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-27
Width: 4.00 in Thick: .412 in Area: 1.65 in^2

Precrack Information

Precrack Date: Jun 15, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 5 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0303 in Bore EDM Length: 0.0044 in

Testing Information

Test Date: Sept 4, 2013 Loading Condition: Variable Amplitude
Constant Load Rate: 140 Kips/sec Spectrum: Baseline B Spectrum
Surface EDM Length: 0.0420 in Hole Diameter .250 in
Peak Stress: 23.04 Ksi

EFH	Crack Length (inches)			
	EDM Side		Opposite Side	
	Front	Back	Front	Back
0	0.042			
91470.39	0.085			
137205.6	0.117			
182940.8	0.1505			
228676	0.1975			
274411.2	0.2555			
304139	0.298	0.004		
324719.9	0.327	0.182		
333866.9	0.3425	0.218		
365881.5	0.403	0.32		
402469.7	0.481	0.4255		
425337.3	0.551	0.499		
443631.4	0.603	0.557		
461925.5	0.6625	0.626		
480219.5	0.7365	0.7075		
498513.6	0.83	0.814	0.124	0.153
508118	0.8905	0.8705	0.18	0.2105
516807.7	0.9745	0.9495	0.2415	0.2775
521381.2	1.014	1.004	0.282	0.321
530528.2	1.158	1.148	0.414	0.441
534973.7	Final Specimen Fracture			

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-28
Width: 4.00 in Thick: .409 in Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 16, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 5 hz Hole Diameter: 0.156 in Peak Stress: 19.5 ksi
Surface EDM Length: 0.0312 in Bore EDM Length: 0.0047 in

Testing Information

Test Date: Mar 2, 2014 Loading Condition: Variable Amplitude
Constant Load Rate: 140 Kips/sec Spectrum: Baseline B Spectrum
Surface EDM Length: 0.0414 in Hole Diameter .250 in
Peak Stress: 23.04 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.0414		0.0000			
185806	0.0633		0.0000			
360030	0.0824		0.0000			
583627	0.11858		0.0000			
772465	0.15376		0.0000			
977761	0.20184		0.0000			
1197855	0.26462		0.0000			
1378902	0.32788	0.14352				
1549388	0.39762	0.29048				
1688747	0.47056	0.38574				
1881776	0.58938	0.53562				
2092317	0.79418	0.7655				
2256435	1.13454	1.13488				
2270026	1.2475	1.205				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-29
Width: 4.00 in Thick: .409 in Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 17, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 5 hz Hole Diameter: 0.156 in Peak Stress: 16.1 ksi
Surface EDM Length: 0.0324 in Bore EDM Length: 0.0045 in

Testing Information

Test Date: Sept 11, 2013 Loading Condition: Variable Amplitude
Constant Load Rate: 140 Kips/sec Spectrum: Baseline B Spectrum
Surface EDM Length: 0.0433 in Hole Diameter .250 in
Peak Stress: 23.04 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.043		0.112			
26593	0.053		0.121			
56467	0.071		0.121			
89204	0.094		0.127			
112826	0.094		0.166			
128092	0.117		0.174			
173189	0.149		0.219			
212170	0.186		0.224			
242343	0.220		0.245			
272791	0.259		0.315			
290604	0.285		0.383			
325531	0.336	0.117				
374632	0.432	0.261				
395772	0.478	0.331				
422695	0.554	0.418				
443350	0.613	0.483				
458555	0.664	0.561				
474135	0.717	0.609				
481853	0.746	0.644				
504162	0.852	0.753				
521701	0.967	0.876				
534735	1.084	1.004				
539575	1.170	1.081				
541754	1.223	1.274				
543121	1.340	1.313				
543632	Final Specimen Fracture					

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-30
Width: 4.00 in Thick: .410 in Area: 1.64 in^2

Precrack Information

Precrack Date: Jun 18, 2013 Loading Condition: Constant Amplitude R=.05
Frequency: 5 hz Hole Diameter: 0.156 in Peak Stress: 16.1 ksi
Surface EDM Length: 0.0317 in Bore EDM Length: 0.0048 in

Testing Information

Test Date: Mar 14, 2014 Loading Condition: Variable Amplitude
Constant Load Rate: 100 Kips/sec Spectrum: Baseline A Spectrum
Surface EDM Length: 0.0438 in Hole Diameter .250 in
Peak Stress: 27.9 Ksi

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.044		0.075			
1045	0.044		0.087			
3238	0.059		0.096			
6719	0.077		0.107			
9192	0.112		0.164			
10800	0.129		0.182			
12675	0.146		0.213			
14457	0.168		0.221			
17279	0.217		0.239			
18210	0.238		0.306			
19330	0.268		0.322			
21009	0.304		0.342			
23270	0.356	0.113				
25782	0.420	0.293				
27679	0.496	0.401				
28924	0.562	0.489				
30065	0.639	0.581				
30825	0.698	0.660				
31262	0.753	0.703				
31875	0.822	0.788				
32534	0.953	0.926				
32738	1.026	0.994				

Fatigue Crack Growth Data Sheet

Specimen I.D. GTOKB003-11-31
Width: ___4.00 in_______ Thick:__.410 in_________ Area: 1.64 in^2

Precrack Information

Precrack Date: July 22, 2013 Loading Condition: Constant Amplitude R=.05_____
Frequency:_5 hz____________ Hole Diameter:0.156 in Peak Stress:19.5 ksi__
Surface EDM Length: 0.0306 in Bore EDM Length: 0.0047 in

Testing Information

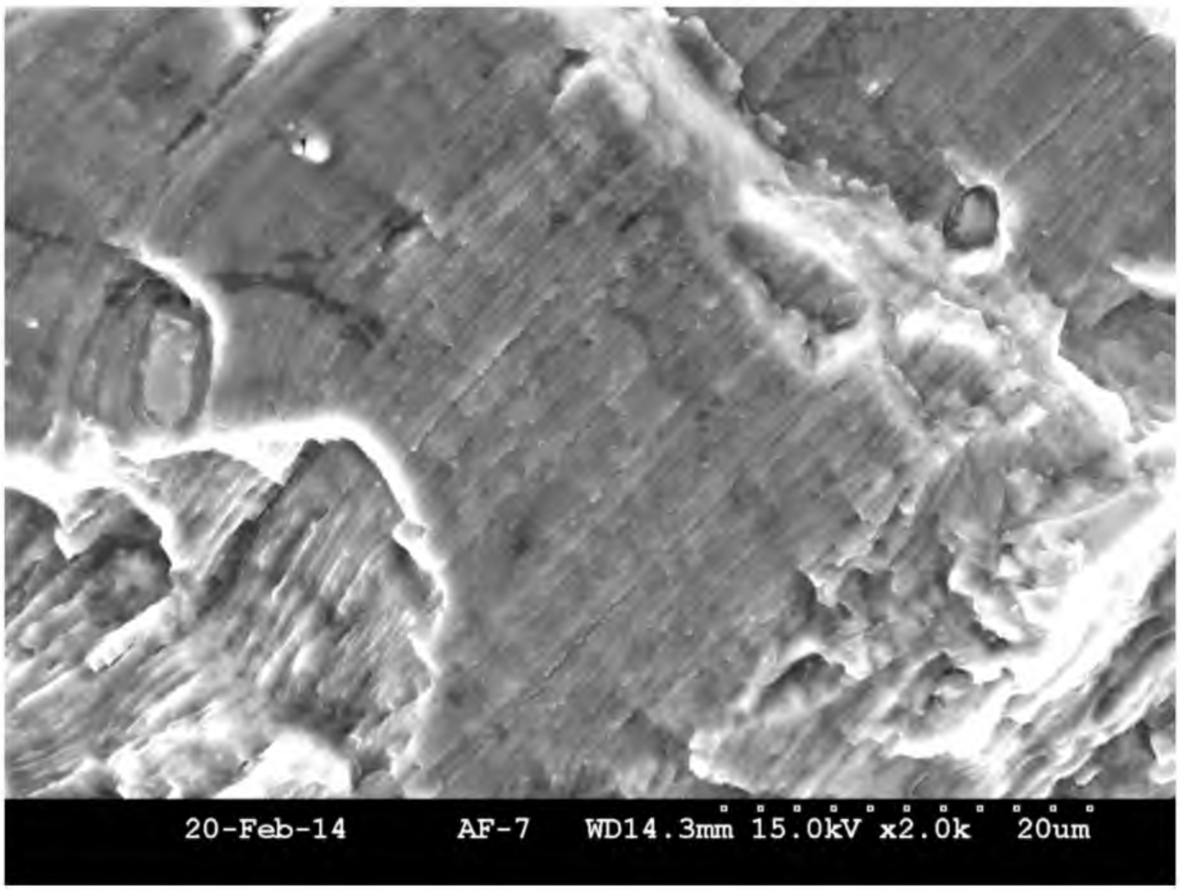
Test Date: Mar 17, 2014 Loading Condition:_Variable Amplitude_
Constant Load Rate:100 Kips/sec Spectrum:__ Spectrum A+B Combination 2
Surface EDM Length:_0.0468 in Hole Diameter .250 in
Peak Stress:__27.9 ksi________

EFH	Crack Length (inches)					Comments
	EDM Side			Opposite Side		
	Front	Back	Bore	Front	Back	
0	0.047		0.094			
2508	0.061		0.117			
5988	0.087		0.144			
8745	0.113		0.167			
11974	0.149		0.216			
14745	0.195		0.286			
16474	0.221		0.328			
21116	0.231		0.328			
27606	0.231		0.328			Switch to B
47549	0.231		0.337			
68879	0.231		0.337			
81852	0.237		0.337			
90133	0.246		0.337			
111212	0.281		0.341			
121940	0.296		0.349			
149728	0.341	0.227				
155010	0.349	0.257				
165341	0.374	0.292				
185822	0.415	0.328				
191861	0.431	0.370				

APPENDIX F

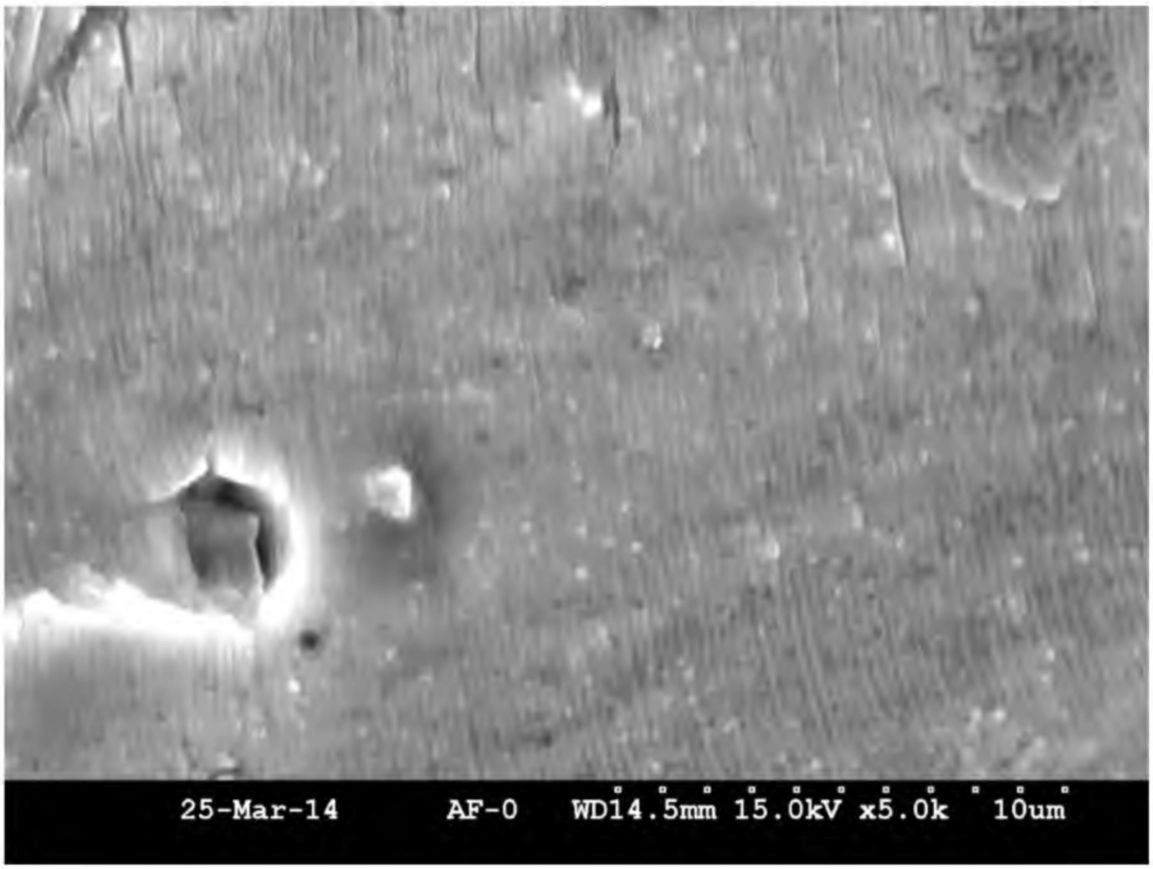
ADDITIONAL SEM IMAGES OF TEST SPECIMEN

FRACTURE SURFACES

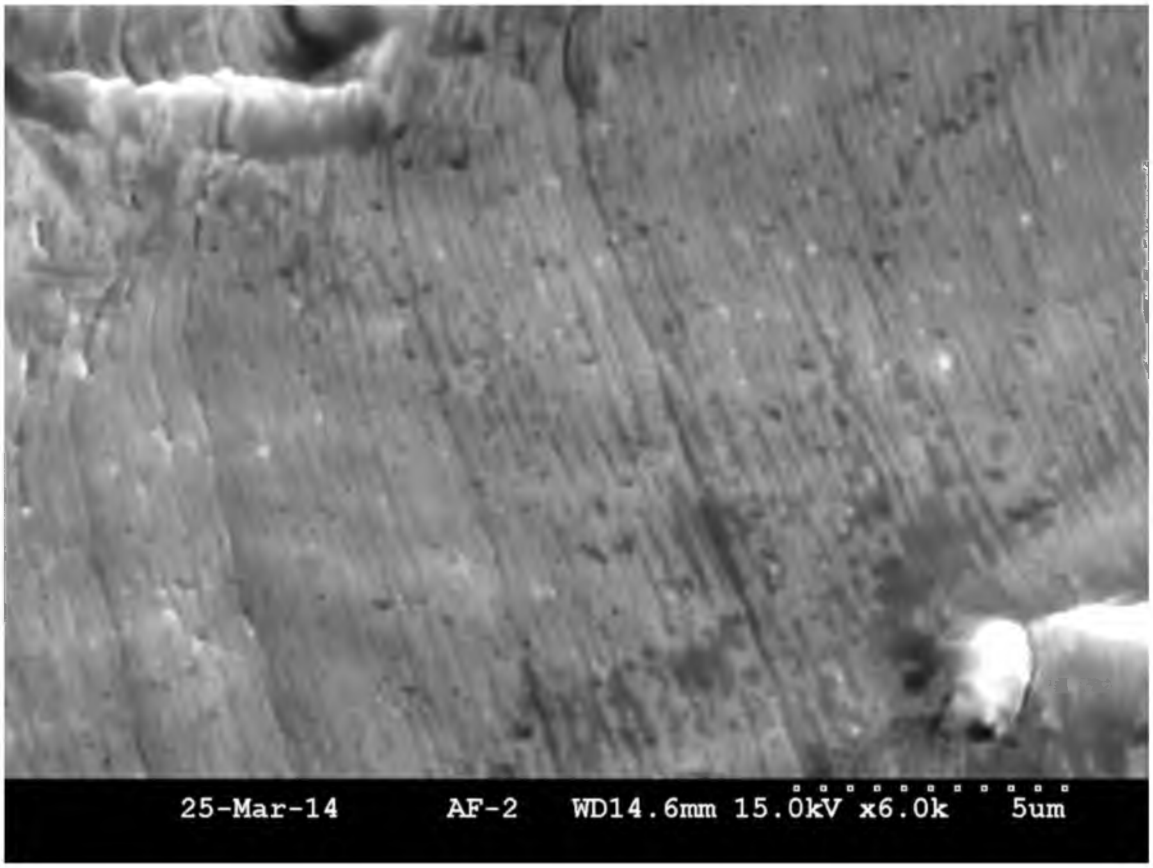


Sample 6 Spectrum B close up showing striation pattern at 2000X magnification

Sample 11 Photograph showing the constant amplitude fatigue striation pattern in the precrack area at 4000 X magnification

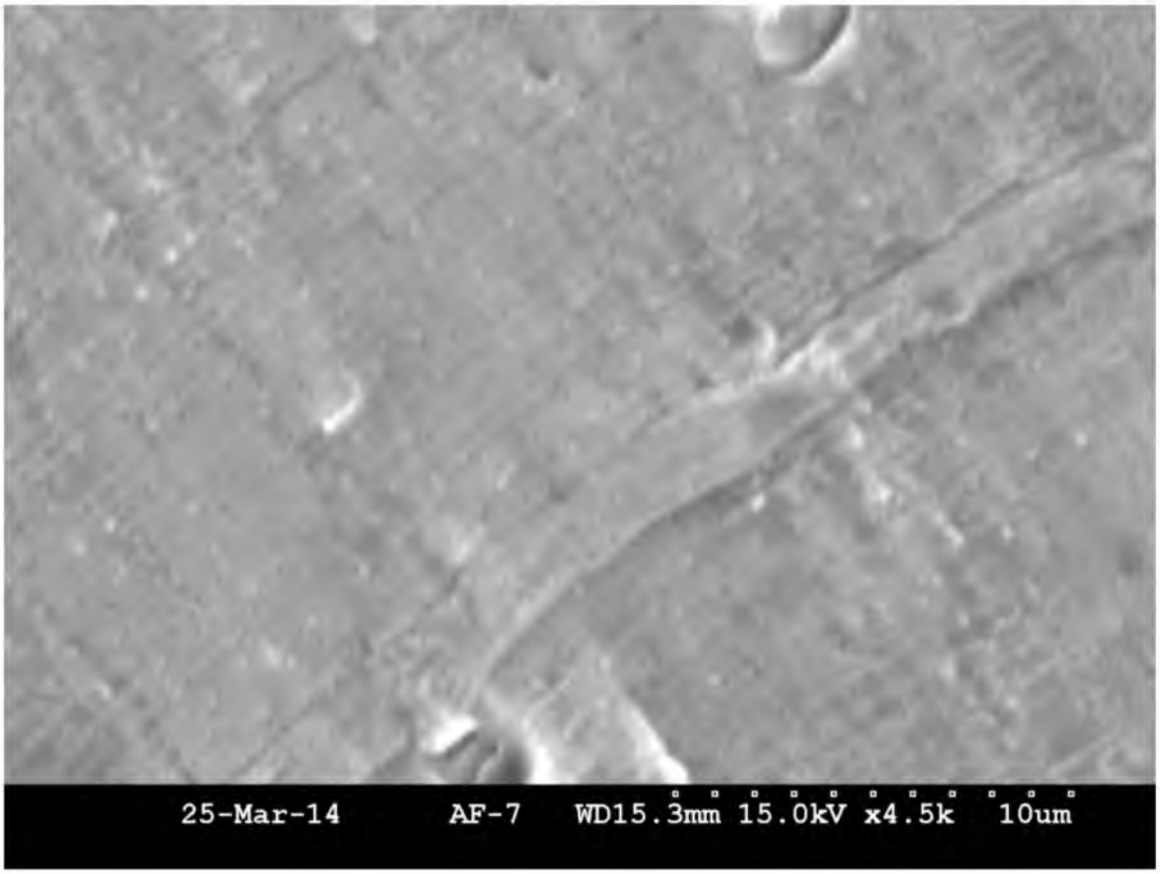


Close up photo of precrack area for Sample 11 at 5000 X magnification



Sample 11 Photo showing the Spectrum A Loading Zone Striation and peak load pattern at 6000 X magnification.

Photograph of striation pattern in Spectrum B Loading Zone at 2000X magnification



Close up showing striations from Spectrum B Loading Zone

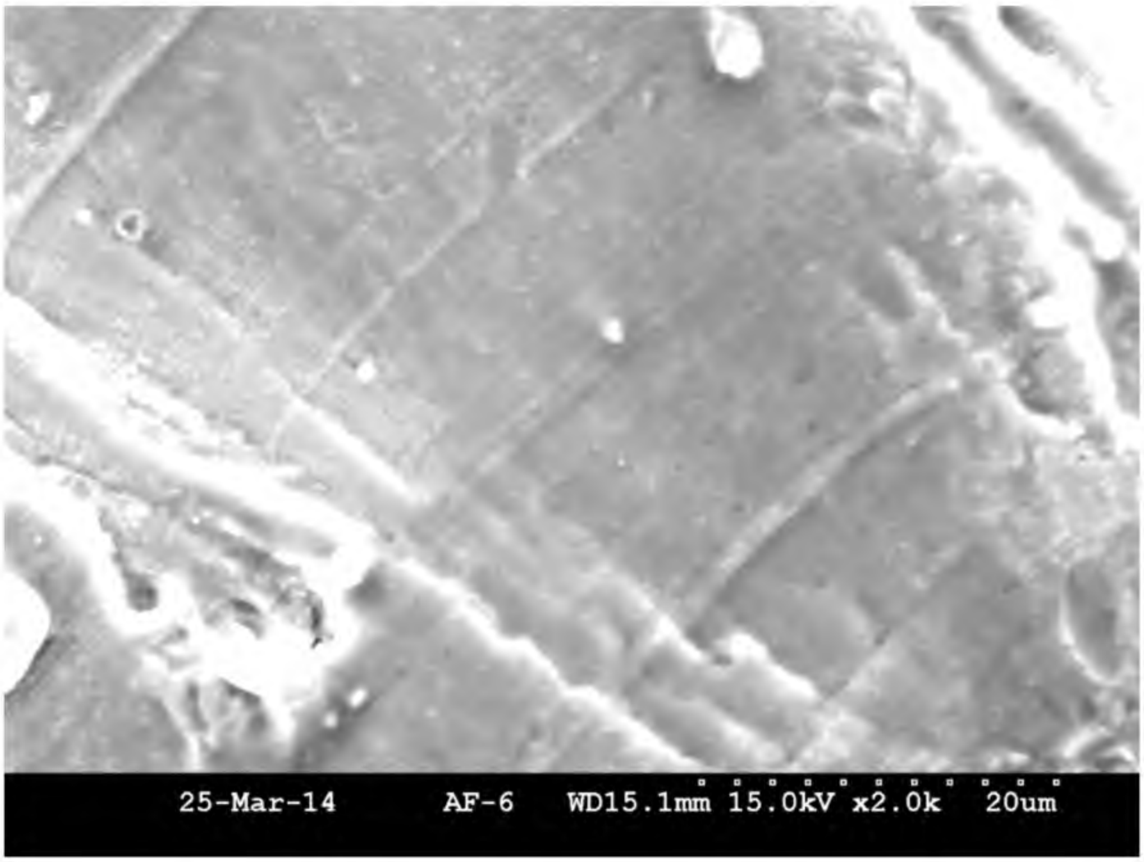
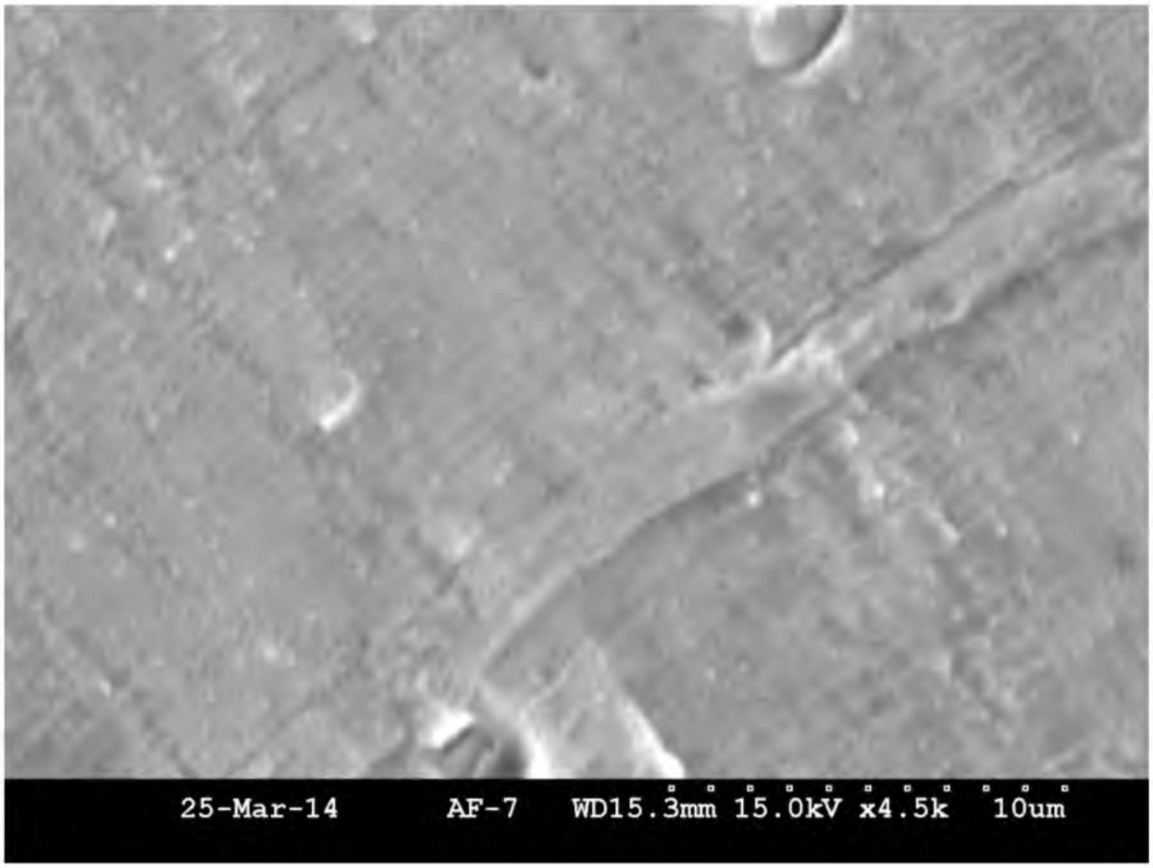
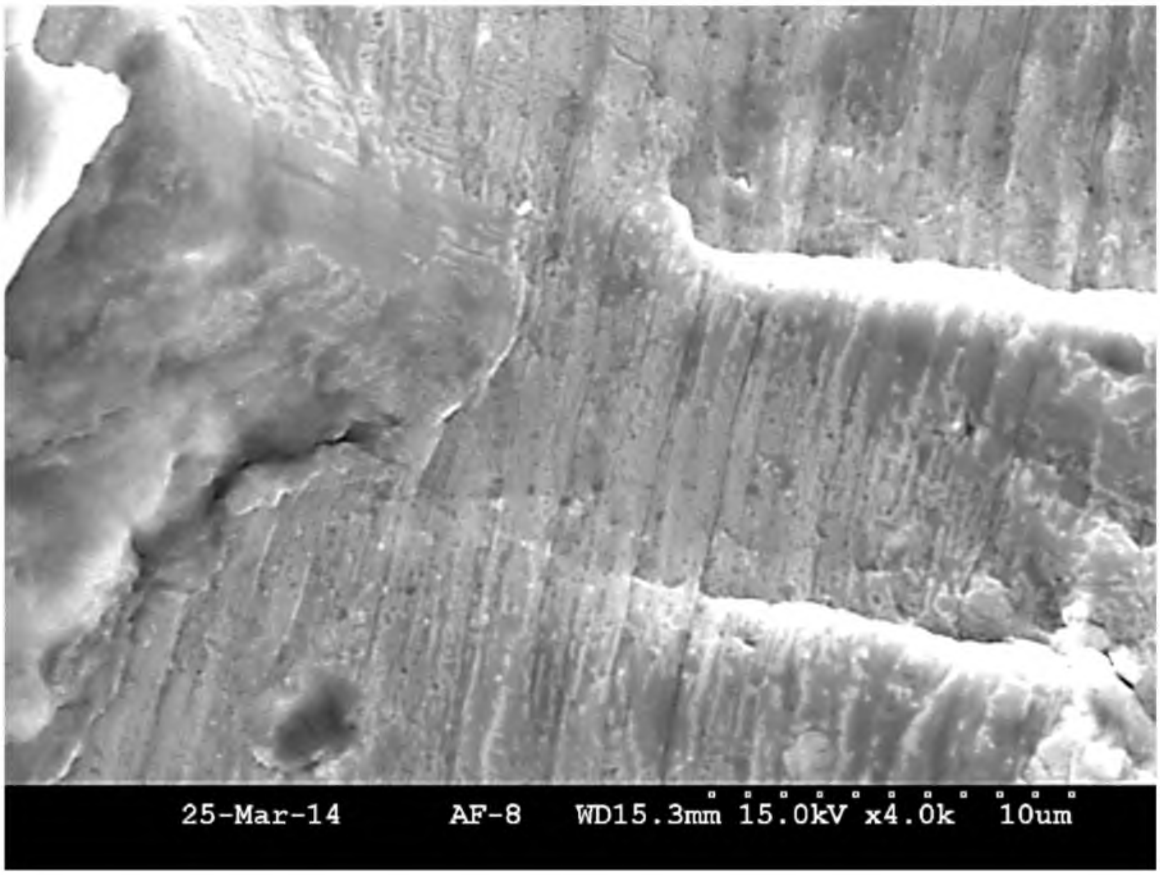


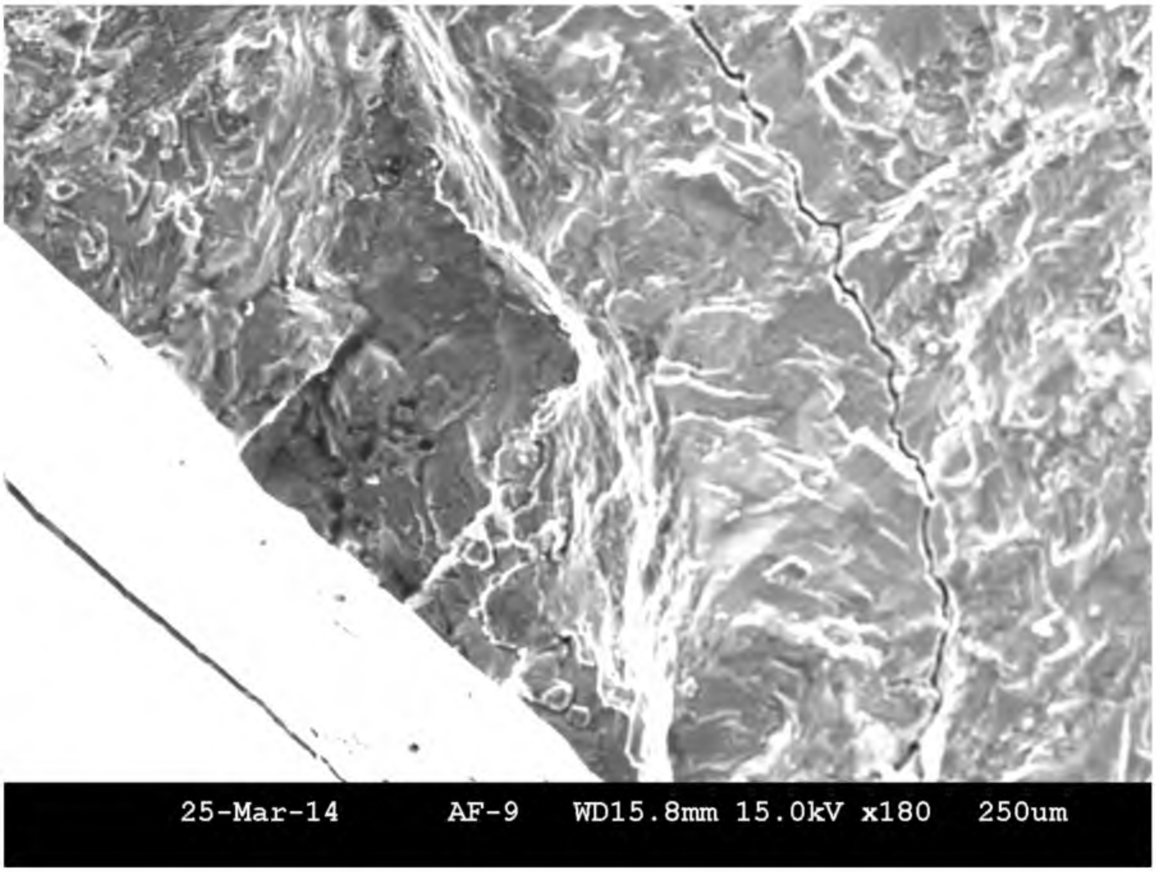
Photo showing striation pattern in Spectrum B Loading Zone for Sample 11 at 2000 X magnification



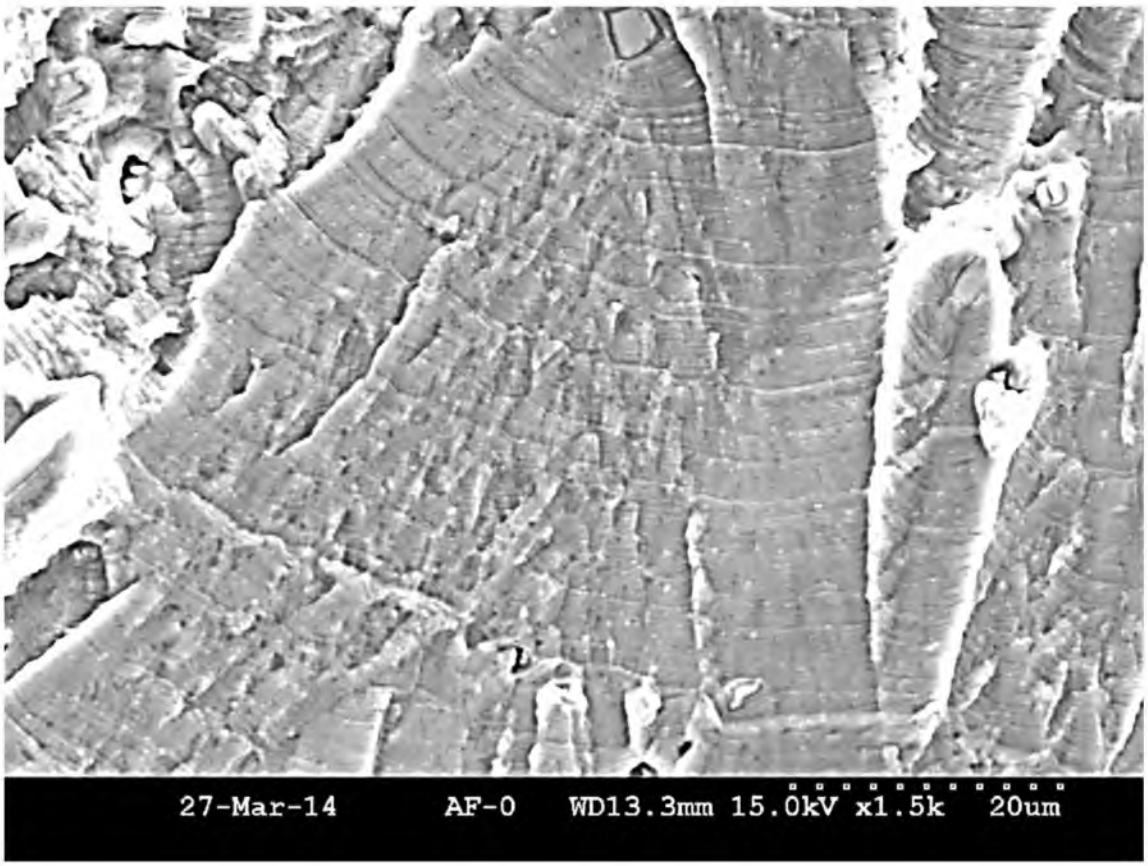
Sample 11 Close up photo of Spectrum B Loading Zone at 4500X magnification



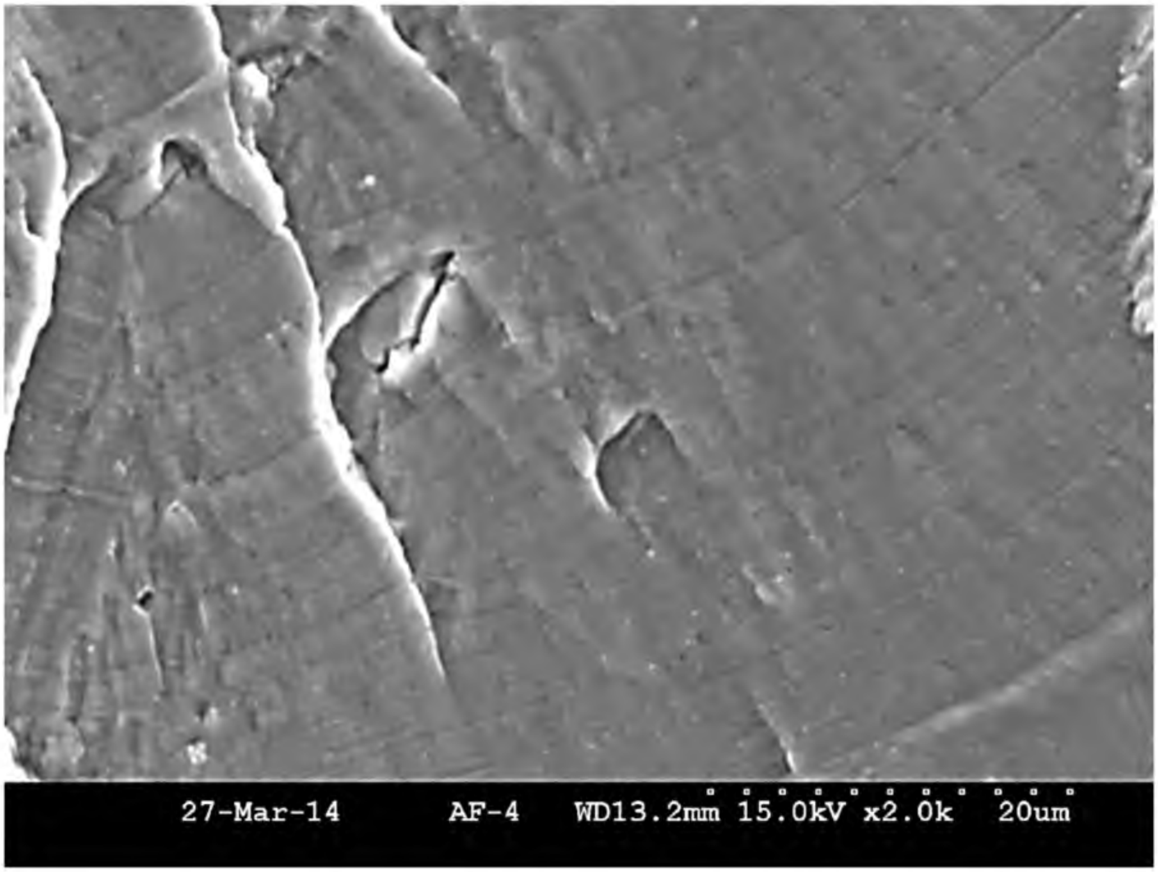
Sample 11 Close up showing striations from Spectrum B Loading Zone



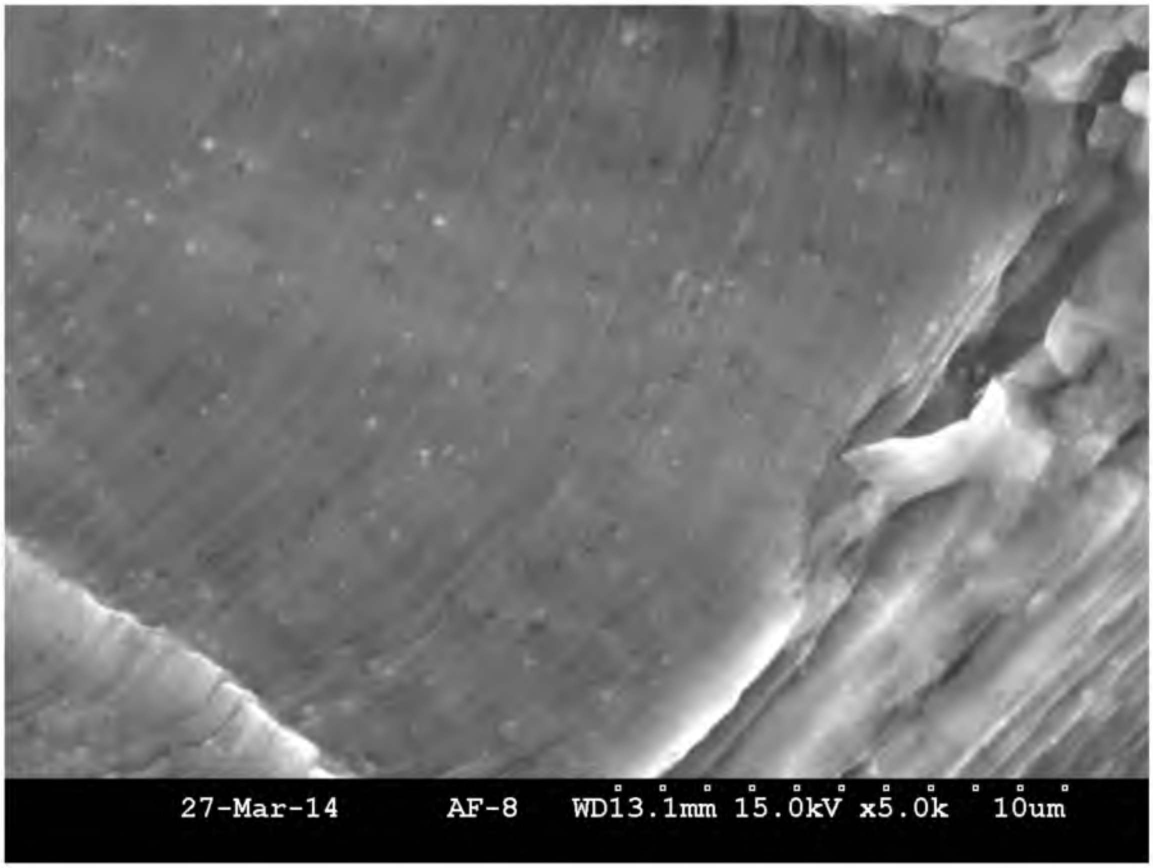
Sample 11 Photograph showing the opposite side of the bore with secondary cracking



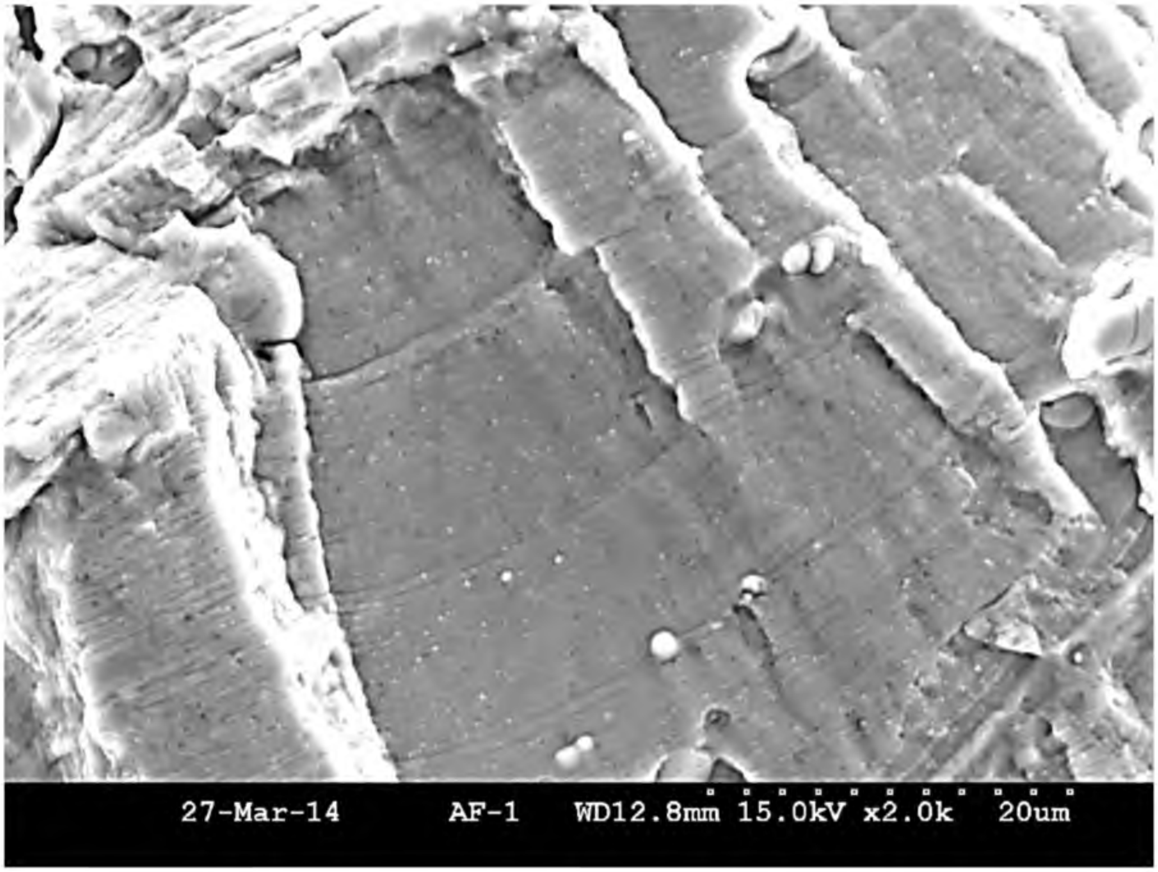
Sample 31 striation pattern under Spectrum A variable amplitude loading



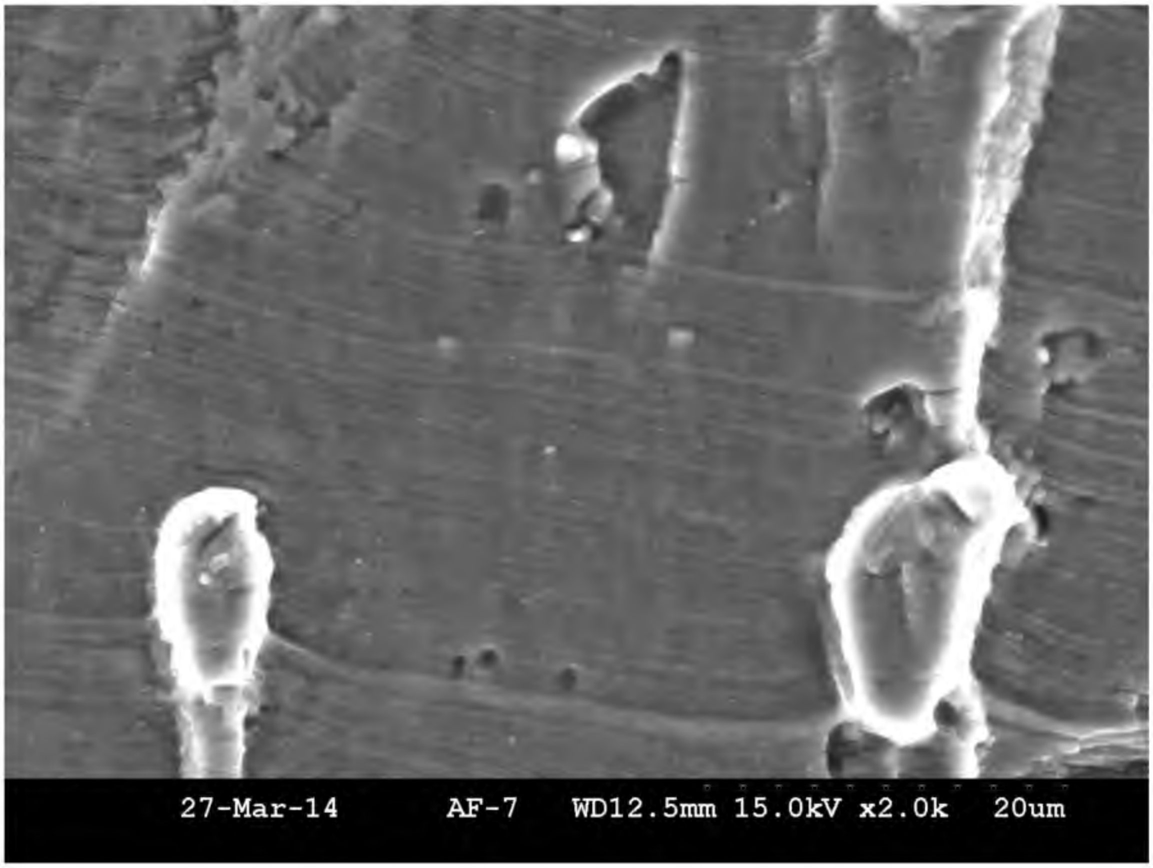
Sample 31 striation pattern under Spectrum A Load Sequence



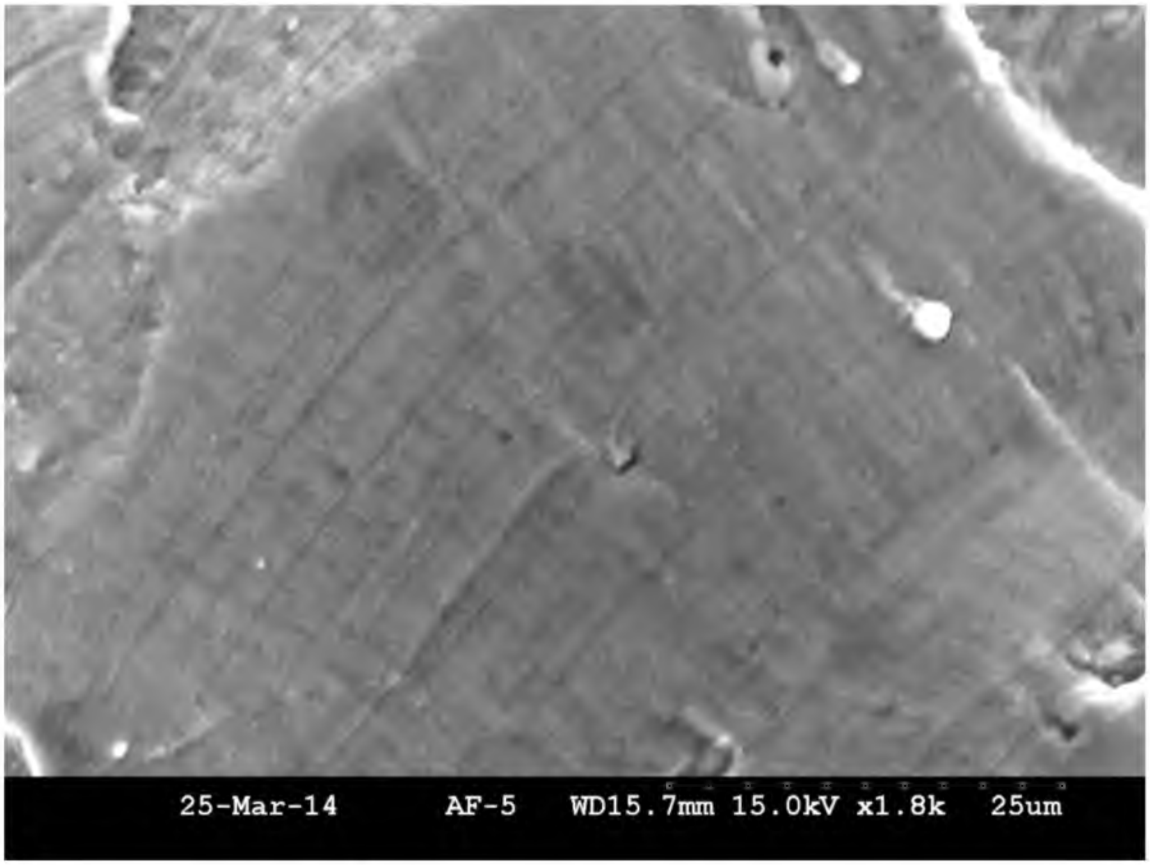
Sample 31 Spectrum B Loading area



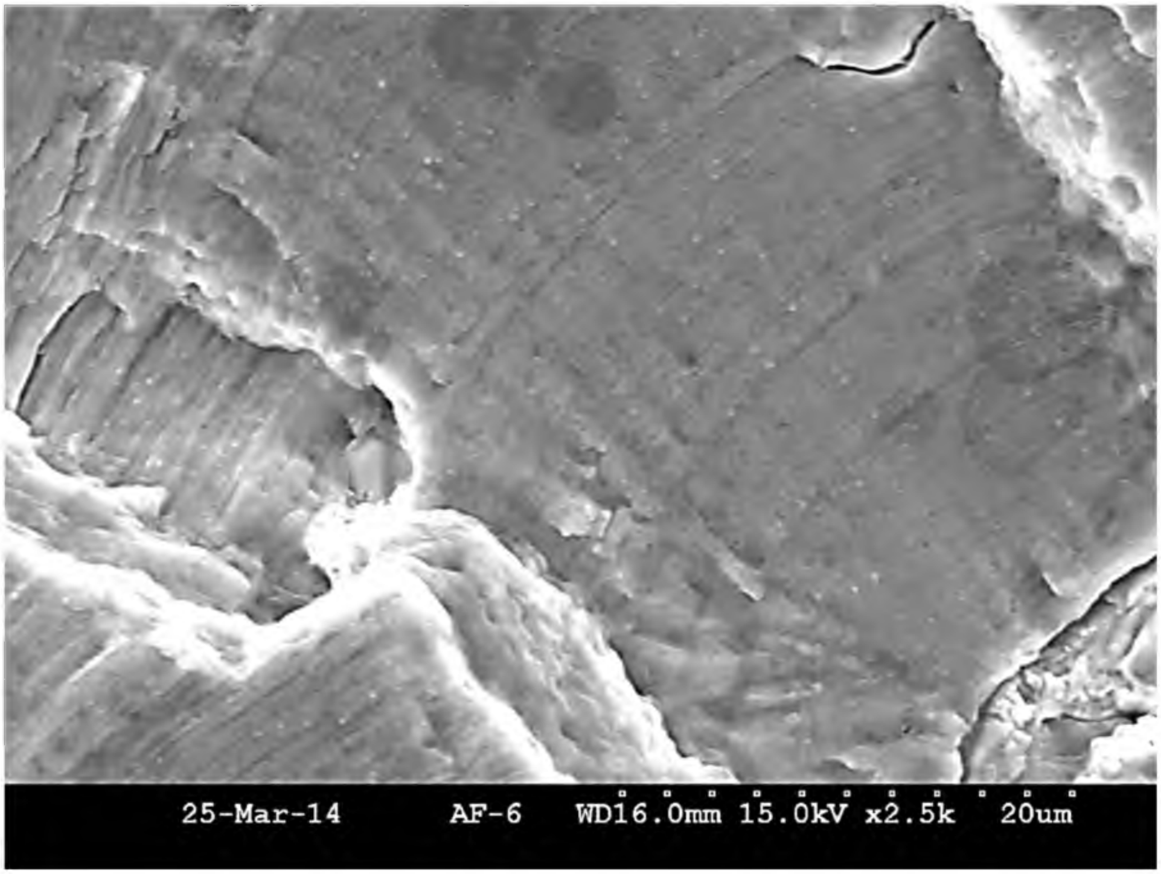
Sample 31 Spectrum B Loading Area



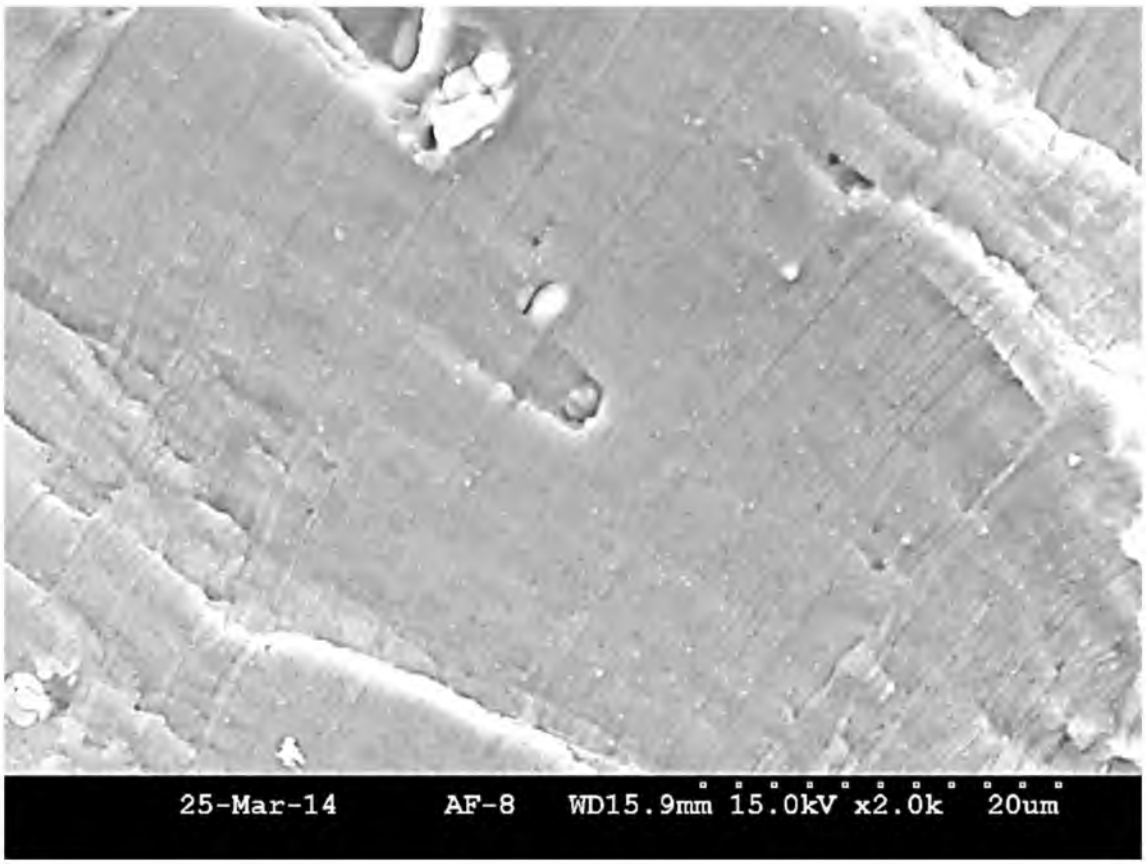
Sample 31 Spectrum A Section



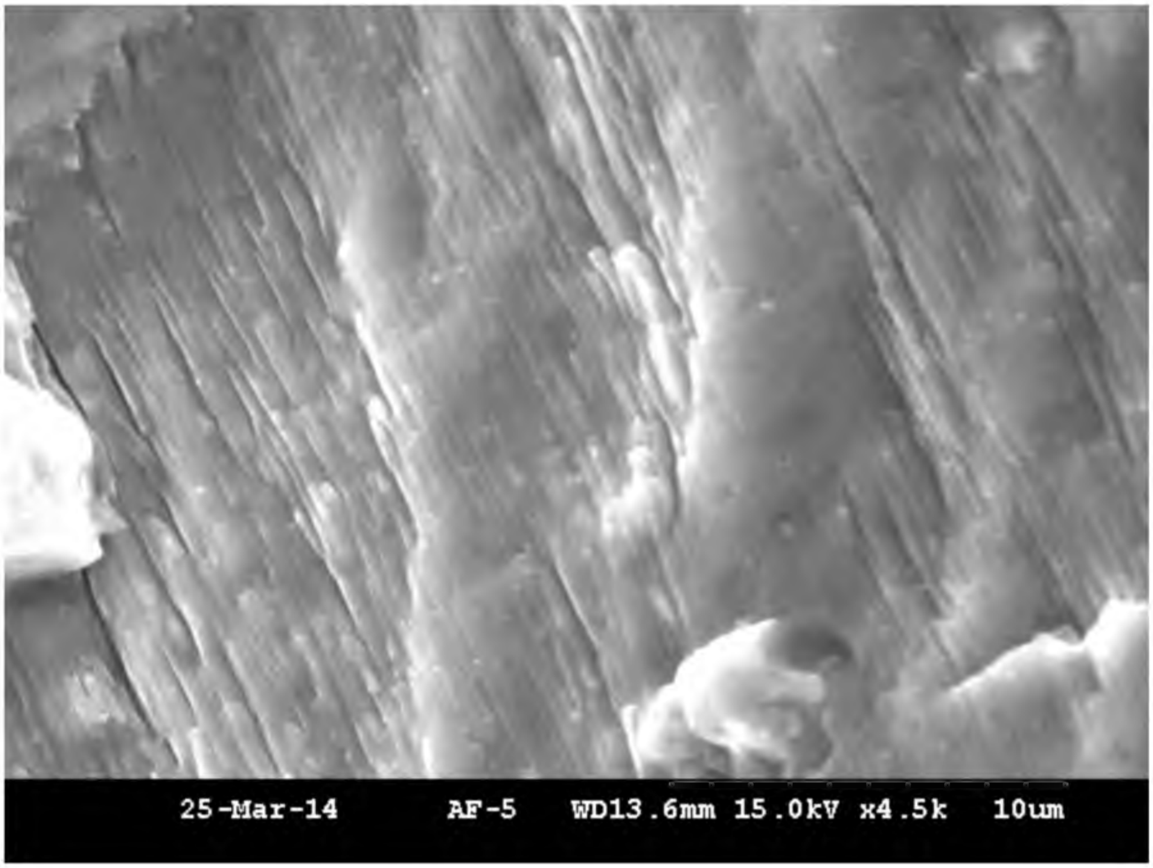
Sample 13 RPDS closeup at 1800 X magnification



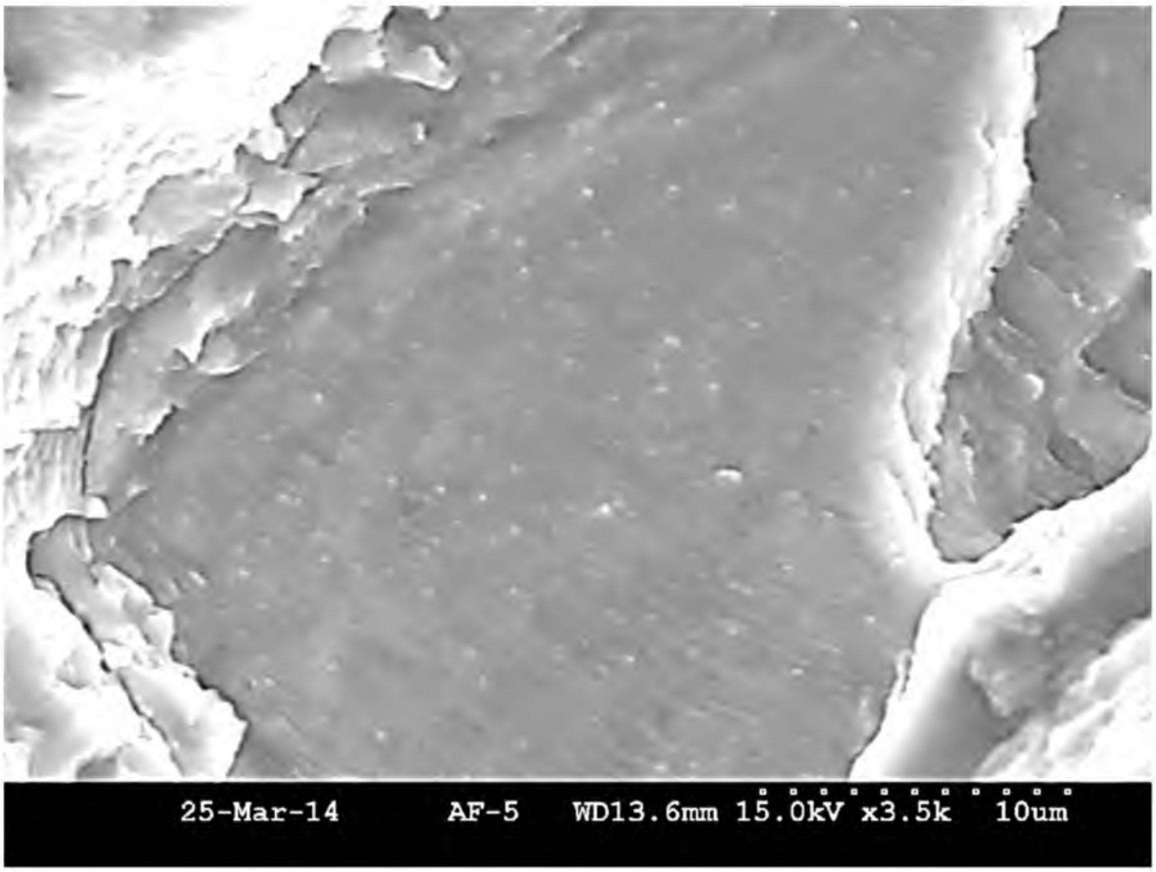
Close up of Sample 13 Spectrum A Loading Zone Striations at 2500X magnification



Sample 13 Spectrum B Loading Zone Striation Pattern at 2000 X magnification

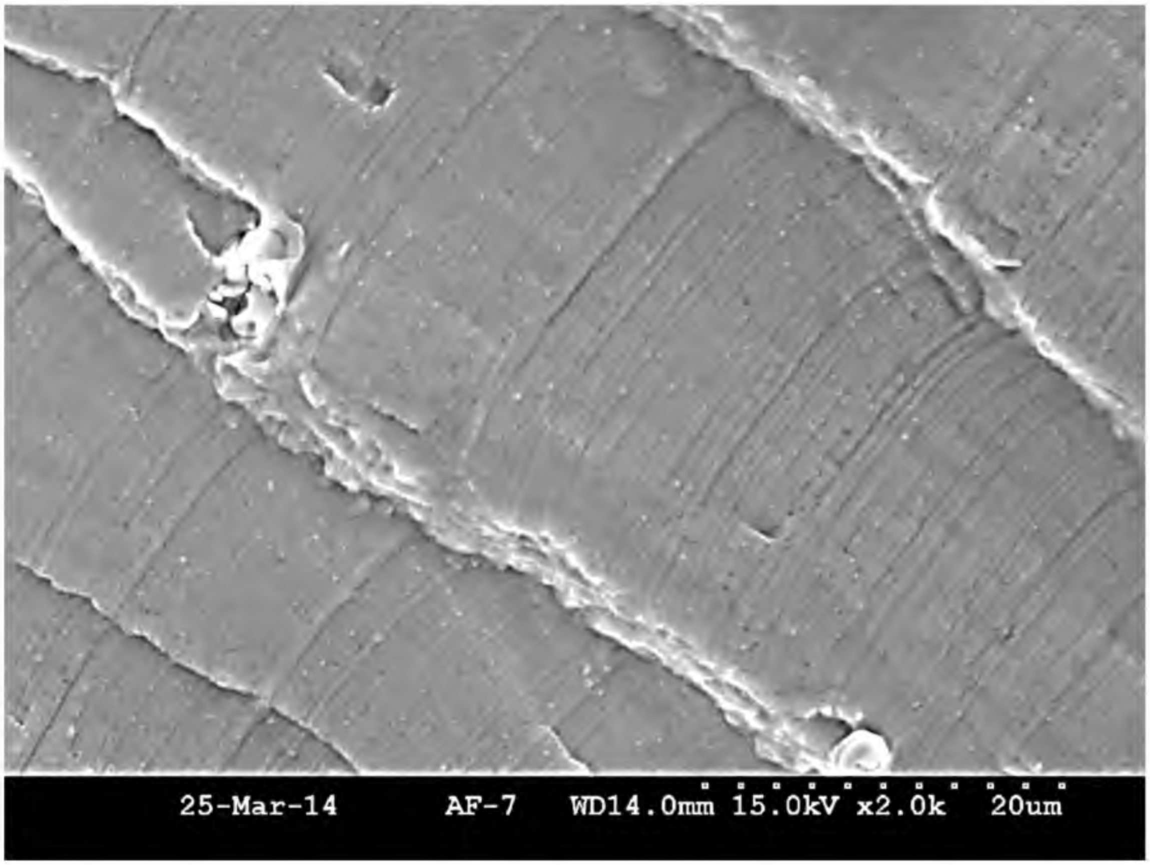


Sample 12 Precrack zone striation count showing constant amplitude loading striations

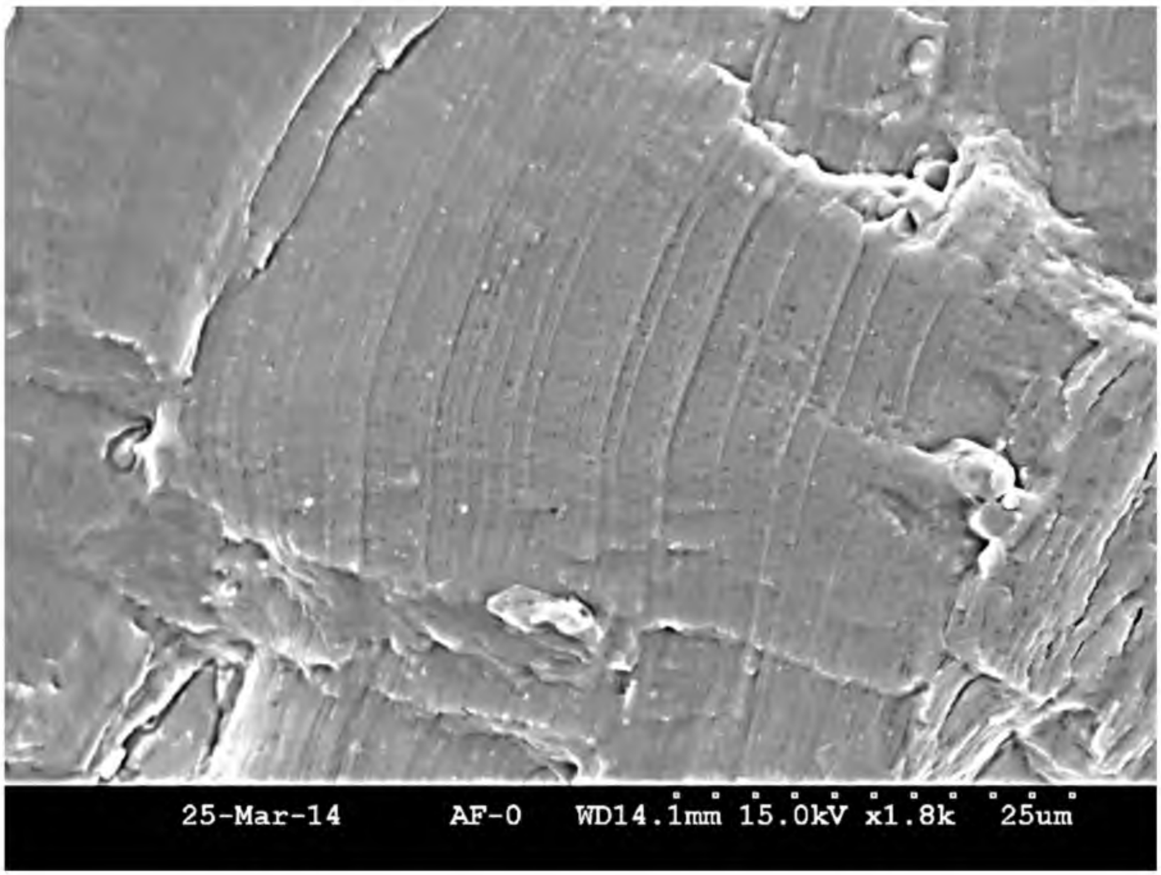


Sample 12 Close up of pre crack zone constant amplitude striations

Photo showing Sample 12 striation pattern with peak loads under Spectrum A loading approximately half way down the bore



Sample 12 Spectrum A Loading striation pattern with peak loads at 2000 X magnification



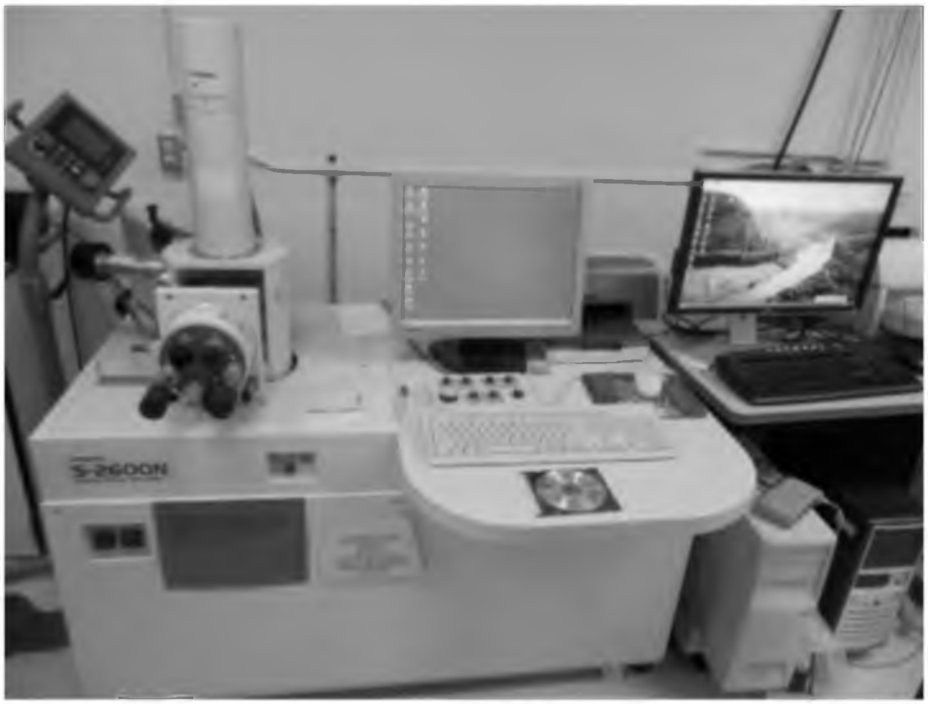
Sample 12 Showing striation pattern under Spectrum B Loading at 1800 X magnification

Striation pattern under Spectrum B Loading at 1800 X magnification

Same Spectrum B area under 4000 X magnification

APPENDIX G

SEM PROCEDURES



Hitachi SEM Model S-2600N

PROCEDURE FOR USING THE SEM

1. Turn on the chiller to the SEM and wait for it to reach a temperature of 68 degrees F.
2. Turn on the power to the SEM.
3. Place the specimen in the vibrating cleaner containing a lacquer solution for 10 minutes.
4. Replace the lacquer solution with one of alcohol for another 10 minutes.
5. Release the vacuum from the observation chamber.
6. Using rubber gloves, place the cleaned specimen into the holding mount, close the chamber and turn on the vacuum pump.
7. Once the vacuum indicator signals that the conditions are sufficient, the electron beam is turned on.
8. Adjust the focus, contrast and brightness until the image is clear. Initially keep a working distance of 15 to 20 mm to obtain a wide view of the surface.
9. Pick a desired location on the surface and magnify the image to 3000X to 4000X and focus the image. This will help produce higher quality pictures at smaller magnifications.

10. Once the image is focused, zoom back out to obtain the widest view desired.
11. Progressively take pictures by incrementally increasing the magnification until the desired amount of detail is obtained.
12. Once the examinations are complete, turn off the elector beam and the pump to release the vacuum from the observation chamber.
13. Using rubber gloves, open the observation chamber and remove the specimen.
14. Close the observation chamber and turn on the pump once more. This will help prevent contaminants from entering the chamber.
15. Once the observation chamber has sufficient vacuum applied, the power may then be turned off to both the SEM and chiller.

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